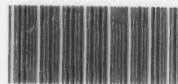


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FEASIBILITY STUDY OF AN EXTENDIBLE
MOBILE ANTENNA TOWER FOR
QUASI-NEAR FIELD MLS MEASUREMENTS
July 1991

Prepared for
Transportation Development Centre
Policy and Co-ordination Group
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SUMMARY

The concept of a mobile Microwave Landing System (MLS) Commissioning Test Facility (CTF) was initially defined in the document entitled "Feasibility Study of an MLS Ground Certification and Measurement Facility" (TP 6501E). This study concluded that the CTF would play a major role in reducing the costs of the commissioning and maintenance of MLS installations by significantly reducing the amount of airborne MLS testing required. A major component of the proposed CTF was a portable, erectable, MLS probe antenna tower system capable of carrying out precision measurements of the MLS system emissions in the Quasi-Near Field region.

The objective of this project was to study the feasibility of using an extendible mobile probe antenna tower combined with a high accuracy position tracker to conduct precision quasi-near field MLS system measurements, and to analyze methods of digitally feeding the probe antenna tracking information into the MLS Commissioning Test Facility processor. In fact, the study was able to go further than its original objective, and carried out a conceptual system design of the Mobile Commissioning Facility, including a design of the CTF major sub-systems.

Mechanical analysis verified that any practically feasible mast system would need to have the probe antenna position tracked to compensate both for uncertainties in the initial mast positioning and for uncertainties in the probe antenna position caused by the wind. It was thus evident that the mast and tracking system must be considered as an integrated system.

Pneumatically extendible telescopic towers were selected as the most appropriate on the basis of their favourable mechanical properties, cost, compactness, and potential ease of use in a practical environment. Such a mast was erected outdoors, and its mechanical and operational parameters observed. A number of design enhancements were proposed to improve its stiffness.

One of the key findings of this study is the importance, if not absolute necessity, of a high precision tracking system to the successful implementation of the Commissioning Test Facility. As it was not possible to locate a suitable off-the-shelf tracking system a conceptual design of an appropriate high precision tracking system was carried out.

The proposed optical tracking system consists of a camera, fixed to a tracking mount, that tracks the angular position of a light fixed to the phase centre of the MLS probe antenna. This system is capable of meeting, or exceeding, the precision requirements, and can be produced from readily available components. Thus, the developmental time and risk are minimized.

Conceptual design of a digital and software interface between the existing MLS Signal Analyzer (representative of the CTF processor) and the proposed tracking system was carried out.

Due to the inter-relationship of the extendible portable mast with all other aspects of the CTF, including the tracking system, the mobile CTF van, and the CTF processor, it was appropriate to go further at this point, and carry out a conceptual design of the complete CTF. The proposed facility consists of a utility van which houses the CTF processor and serves as a support for the extendible antenna mast, and a tracking system located close to the MLS antenna. Data and instructions are passed between the van and the tracking system by way of a telemetry link.

This study concludes that a movable, erectable antenna tower is feasible when used in conjunction with an appropriate tracking system, and that such a tower and tracking system can be built with commercially available components with minimal development effort and risk.

Furthermore, conceptual designs of the Commissioning Test Facility and all of its major sub-systems have been carried out, and been shown to be feasible.

Sommaire

Le concept d'une installation d'homologation du système d'atterrissage hyperfréquences MLS a été défini pour la première fois dans le document intitulé "Étude de faisabilité d'une installation d'homologation et d'essai au sol pour système MLS" (TP6501E). L'étude avait montré que cette installation permettrait de réduire considérablement les coûts d'homologation et de contrôle périodique des installations MLS par la réduction du nombre de vols de contrôle à effectuer. Cette installation, s'articulant autour d'une antenne sonde placée au sommet d'un mât télescopique mobile, devait être destinée à effectuer le mesurage de précision des signaux rayonnés par un émetteur MLS dans les champs intermédiaires.

La présente étude avait pour objectif d'examiner la possibilité d'utiliser un mât mobile et télescopique supportant une antenne sonde, associé à une unité de repérage de précision pour effectuer les opérations de vérification requises. L'étude devait aussi proposer des méthodes numériques pour le transfert de l'information fournie par l'unité de repérage vers le processeur de l'installation d'homologation. En réalité, l'étude, dépassant l'objectif initial, a débouché sur l'étude conceptuelle de ladite installation et des principaux organes qui la composent.

L'analyse du point de vue mécanique du mât de l'antenne a mis en évidence la nécessité du repérage de précision de l'antenne sonde, et ce, pour tenir compte des déplacements du mât par rapport à sa position initiale et ceux de l'antenne sous l'effet du vent. Il était clair qu'il fallait considérer ces deux fonctions comme formant un seul ensemble et qu'il fallait les étudier du point de vue systémique.

Un mât à mécanisme de coulissement pneumatique a été choisi parce qu'il a été jugé le meilleur par sa mécanique, son coût, son faible encombrement et sa facilité d'emploi en service. L'observation des paramètres mécaniques et fonctionnels du mât placé à l'extérieur a mené à des modifications destinées à en accroître la raideur.

L'étude a mis en évidence la grande importance, sinon l'absolue nécessité, du repérage de précision de la position de l'antenne, sans quoi la fiabilité de l'installation d'homologation risquait d'être compromise. Il a donc fallu procéder à l'étude conceptuelle de cette unité de repérage, étant donné qu'il a été impossible d'en trouver l'équivalent sur le marché.

L'unité proposée comporte une caméra montée sur une base pivotante, permettant de situer la position angulaire exacte d'un feu fixé en un point qui correspond au centre de phase de l'antenne sonde. Cette unité, dont la précision s'est révélée égale sinon supérieure à la précision requise, peut être assemblée à partir d'éléments faciles à obtenir. Ainsi, sa mise au point entraîne des délais et des risques d'exécution réduits au maximum.

Les chercheurs ont également fait l'étude conceptuelle de l'interface numérique entre l'analyseur des signaux MLS (représentant le processeur de l'installation d'homologation) et l'unité de repérage de précision proposée.

En raison de l'indissociabilité du mât télescopique, d'une part, et de tous les autres éléments de l'installation d'homologation (unité de repérage, camion transportant le mât et processeur), d'autre part, les chercheurs ont jugé approprié de procéder à l'étude conceptuelle de l'installation d'homologation dans son ensemble. Ils proposent une formule comportant un camion qui, en plus d'abriter le processeur, supporte le mât télescopique et une unité de repérage placée à proximité de l'émetteur MLS. Des liaisons télémétriques sont prévues entre le camion et l'unité de repérage.

L'étude a montré que l'installation d'homologation formée du mât mobile et télescopique et de l'unité de repérage étudiée en fonction de celui-ci était techniquement faisable, que l'un et l'autre pouvaient être assemblés à partir d'éléments sur le marché et que leur réalisation entraînerait des délais et des risques d'exécution réduits au maximum.

Enfin, on a fait une étude conceptuelle de l'installation d'homologation et de ses principaux éléments constitutifs, laquelle a été jugée faisable.

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1.0 INTRODUCTION

The concept of a mobile Microwave Landing System (MLS) Commissioning Test Facility (CTF) to carry out detailed ground based analysis of MLS systems was initially defined in the document entitled "Feasibility Study of an MLS Ground Certification and Measurement Facility" (TP 6501E). This study concluded that the CTF would play a major role in reducing the costs of the commissioning and maintenance of MLS installation by significantly reducing the amount of airborne MLS testing required. A major component of the proposed CTF was a portable, erectable, MLS probe antenna tower system capable of carrying out precision measurements of the MLS system emissions in the Quasi-Near Field region.

The objective of this project was to study the feasibility of using an extendible mobile probe antenna tower combined with a high accuracy position tracking to conduct precision quasi-near field MLS system measurements, and to analyze methods of digitally feeding the probe antenna tracking information into the MLS Commissioning Test Facility processor. In fact, the study was able to go further than its original objective, and carried out a conceptual system design of the Mobile Commissioning Facility, including a design of the CTF major sub-systems.

Mechanical analysis indicated that it was not practical to implement a mast system that could be positioned to the required precision without use of a tracking system. Furthermore, analysis indicated that once positioned, the only practical mast systems that would not sway in wind to the degree that the positional tolerances were exceeded were guyed towers. This type of system had to be ruled out due to airport safety concerns.

Consequently, analysis verified that any practically feasible mast system would need to have the probe antenna position tracked to compensate both for uncertainties in the initial mast positioning, and for uncertainties in the probe antenna position caused by the wind.

A survey of erectable, portable, antenna towers was carried out, and certain classes of towers were identified and considered. From amongst the candidate towers, sectioned, pneumatically extendible towers were selected as the most appropriate, on the basis of their favourable mechanical properties, cost, compactness, and potential ease of use in a practical environment.

Experiments on a representative mast were then carried out to determine and characterize the motion of the antenna mast, and mock antenna assembly under windy conditions. The stiffness and resonant frequency of the mast was determined, and its motion on a number of windy days was observed. It was found that the mast was not as stiff as expected and, consequently, it swayed more than expected. Investigation indicated that the lack of stiffness was a result of the design of the joiners used to link the mast segments. A more suitable joint was designed to alleviate this problem. Furthermore, it was found the motion of the mast due to wind could be further reduced by the use of a tension cable joining the top of the mast to the mobile CTF van.

Conceptual and preliminary design of the antenna mast, the joint stiffeners, and the probe antenna multi-path fine motion mechanism were carried out. The fine motion mechanism is capable of moving the MLS probe antenna continuously over a ± 1.5 m distance to aid with the identification of multi-path effects.

One of the key findings of this study is the importance, if not necessity, of a high precision tracking system to measure the position and the motion of the MLS probe antenna. The precision required, and the range of angles and distances over which the tracking system must operate, are such as to preclude the purchase of an off-the-shelf commercially available system.

A number of differing types of tracking systems were identified and considered. The preferred option was based on an optical tracking camera that tracked a target light fixed to the MLS probe antenna. It was shown to be capable of meeting the system precision requirements, and the basic tracking system components are available off the shelf. Consequently, this system represents the least developmental effort and risk.

This system has a number of distinct features which make it well suited to use within the CTF system. It inherently tracks and measures the angular position of a tracking light as it would be observed by the MLS antenna under test. If the tracking light was placed at the phase centre of the probe antenna, as would be possible for an appropriately designed planar micro-strip antenna, the angular coordinates measured would not depend on the angle that the probe antenna makes with respect to MLS transmitting antenna. This is important since rotational angular motion of the mast antenna due to the wind would, in principle, slightly alter the normally parallel orientation of these two antenna, potentially resulting in tracking errors if the tracking light is not at the phase centre of the probe antenna.

The camera consists of a lens that focuses an image of the

tracking light onto a CCD array. To reduce the effect of false targets, a tracking light of a particular optical frequency, or colour, could be selected, and the camera fitted with a corresponding band-pass filter.

The combination of the lens focal length, and of the CCD pixel size can be selected so as to yield, in principle, arbitrary angular precision. In the proposed system, this combination is selected such that a deflection of the mast by the maximum tolerable angular error (0.005°), results in a shift of the image of tracking light on the CCD array by a displacement which is easily detectable and provides sufficient overall tracking system resolution.

The tracking system as proposed is capable of tracking the motion of the tower over a 2° angle, which corresponds to a 1.5 m window at the location of the tower. To achieve initial alignment of the optical tracking window with the antenna tower, the CTF operator would instruct the tracking system via a telemetry link to move to one of a number of predefined angular positions.

Detailed analysis of methods to digitally interface the tracking system to the CTF processor were considered. As the CTF processor is not yet designed, the existing MLS Signal Analyzer processor was used as a model. A conceptual and preliminary design of a digital and software interface between the proposed tracking system and the MLS Signal Analyzer was carried out.

Due to the inter-relationship of the extendible portable mast with all other aspects of the CTF, including the tracking system, the mobile CTF van, and the CTF processor, it was appropriate to go further at this point, and carry out a conceptual design of the complete CTF. The proposed facility consists of a utility van which houses the CTF processor and serves as a support for the extendible antenna mast, and a tracking system which is located in close proximity of the MLS antenna. Data and instructions are passed between the van and the tracking system by way of a telemetry link.

The proposed system is capable of being operated by a single technician. The operator would move the truck to a predefined location, extend the mast to a predefined height, stabilize the van, take the required MLS measurement, then restore the van to a movable condition, and move on to the next location. This sequence would be repeated until all of the required measurements had been performed. The data so collected would then be analyzed to yield the required MLS system requirements.

This study concludes that a movable, erectable antenna tower is feasible when used in conjunction with an appropriate tracking system, and that such a tracking system can be built

with commercially available components with minimal development effort and risk.

Furthermore, conceptual designs of the Commissioning Test Facility and all of its major sub-systems have been carried out, and been shown to be feasible.

2.0 ANTENNA TOWER INVESTIGATION

An investigation was conducted to define the requirements of the mast, evaluate candidate tower concepts and prepare an evaluation matrix.

2.1 REQUIREMENTS

- a. Height of the antenna - Capable of extension from 3.05 m to 15.25 m above ground
- b. Accuracy of the antenna location - $\pm 0.005^\circ$ when viewed from the MLS antenna. This equates to ± 3 mm lateral position accuracy for the azimuth case and fore and aft accuracy of ± 9.3 mm to give a vertical accuracy of ± 3 mm.
- c. Operability - capable of erection and retraction by one person in 2 minutes
- d. Mobility - capable of being easily erected, retracted and re-erected on a predefined measuring grid in the MLS antenna near field
- e. Transportability - capable of being shipped by air or road to other airfields
- f. Capable of operating in 30 km/h winds and safe in 50 km/h gusts
- g. Mast should not be guyed to fixed points
- h. The mast must be safe to operate.
- j. Cost

2.2 CANDIDATE MASTS

Various existing mast concepts were considered:-

- a. Scissors type man-lift
- b. Cherry picker man-lift
- c. Telescopic hydraulic crane
- d. Pneumatic telescopic mast

2.2.1 Erection and Retraction Capabilities

a. Scissor Type Man-lift

Review of this approach showed that erection and retraction would be simple and straightforward. Also, the mechanism retracted to a low profile. A relatively low power hydraulic system would be required for raising and lowering.

b. Cherry Picker Type Man-lift

This concept also would provide simple erection and retraction, again the retracted profile would be low. A low power hydraulic system would be required.

c. Telescopic Hydraulic Crane

This approach can easily meet the requirement for ease of erection, and retraction, and provides a low profile when retracted. A medium power hydraulic system would be required.

d. Pneumatic Telescopic Task

This is very easy to erect and retract but when retracted the mast is still fairly high. A small (1/4 HP) air compressor and tank would provide quick erection capability.

2.2.2 Mechanical Properties

Analysis indicated that none of the candidate masts could provide the required location accuracy without guying (refer to Appendix A). Therefore the concept of using a tracking system was deemed essential. With the use of a tracking system the mechanical properties of the mast become relatively unimportant providing the mast position remains within the tracking system capabilities. This means that the emphasis can be placed on factors such as the masts ease of operation and cost.

2.2.3 Mobility

Each of the mast concepts would meet the requirement of erection, retraction and re-erection on a predefined grid.

2.2.4 Transportability

Each candidate mast was reviewed to determine its transportability on the airfield, between airports by road and by air.

a. Scissors Type Man-lift

A mast of this type to reach 15.25 m has a fairly large platform and thus would require mounting on a trailer or light flatbed truck.

The low profile of a retracted scissor lift means that transportability on the airfield and on the road is good.

The mechanism could easily be palletized so that air transportation is practicable.

b. Cherry Picker Man-lift

A cherry picker with a 15.25 m height capability will require both arms of the mechanism to be very long, i.e., about 9.15 m. This means it must be mounted on a long trailer. Transportation on the airfield or road would be satisfactory but air transportation would require a cargo plane.

c. Telescopic Hydraulic Crane

A 15.25 m crane of an off-the-shelf design is heavy and requires a large truck with reinforced chassis to carry it. Transportability on the airfield and on the road would be satisfactory but air transportation would require a large cargo aircraft such as a C130.

d. Pneumatic Telescopic Mast

This is easily transportable on the airfield but because of its high profile in the retracted state it cannot be transported by road with the mast in its mount. This problem is taken care of by use of a mount which allows the mast to be lowered and stowed horizontally on the roof of a medium-sized van. Mounts of this type are standard accessories for most makes of mast. This is illustrated in figure 5.1.

Transportation by air is easily achieved as the mast is only about 3.36 m long and weighs about 45.45 kg.

2.2.5 Capability of Operating in 30 Km/h Winds and
Safe in 50 Km/h Gusts

All of the candidate systems appear to be capable of operating under the required conditions. The scissor lift system incurs high windage and so would require extra stabilization from the vehicle on which it is mounted. None of the concepts would require guying to fixed points.

2.2.6 The Mast Must be Safe to Operate

a. **Scissor Type man-lift**

This mast comprises a large number of levers and joints which could cause injury during erection or retraction. Acceptable safety could be achieved with suitable guards and interlocks.

b. **Cherry Picker Man-lift**

This mechanism does have some areas which could be hazardous. Guards and interlocks could achieve satisfactory safety.

c. **Telescopic Hydraulic Crane**

This is similar to the cherry picker from the safety point of view.

d. **Pneumatic Telescopic Mast**

This is inherently safe, the only moving parts are out of reach and are very light. No large forces are required to raise or lower it.

2.3 **COST COMPARISON**

No detailed costing has been carried out but order-of-magnitude estimates have been used for comparison purposes only.

a. **Scissor Type Man-lift**

Cost of mechanism	\$20,000
Cost of mount and accessories	\$20,000
Custom design required	

b. Cherry Picker Man-lift

Cost of mechanism \$20,000
 Cost of Mount & Accessories \$20,000
 Some custom design required

c. Telescopic Hydraulic Crane

Cost of mechanism \$20,000
 Cost of mount & Accessories \$30,000
 Some custom design required

d. Pneumatic Mast

Cost of Mast \$10,000
 Cost of mount & Accessories \$5,000
 Off-the-shelf design

2.4 EVALUATION MATRIX

An overview of the evaluation conducted on each of the candidate tower concepts is summarized in Table I.

Table I - Summary of Candidate Tower Concepts

Mast Type	Operating	Mobility	Transport Ability		Safety	Design Required	Cost
			Road	Air			
Scissors Type	Good	Good	Good	Fair	Fair	Custom	\$40,000
Cherry Picker	Good	Good	Good	Fair	Fair	Semi-Custom	\$40,000
Telescopic Crane	Good	Good	Good	Poor	Fair	Semi-Custom	\$50,000
Pneumatic Telescopic	Good	Good	Good	Good	Good	Standard	\$15,000

This summary is based on the following assessments; details are provided in Paragraphs 2.2 and 2.3: -

- Good - Fully meets requirements with no special procedures or precautions.
- Fair - Fully meets requirements providing special procedures or precautions are carefully observed.
- Poor - The requirement can be met but involves difficulty.

2.5 CONCLUSION

The pneumatic mast was assessed to be clearly the best choice for the MLS calibration application. This choice was based on ease of use, potential reliability, lower cost, easy attachment to the vehicle, minimal maintenance requirements, compactness and lightness for shipping.

2.6 RECOMMENDATION

Conduct test program using the pneumatic mast.

3.0 ANTENNA MAST EXPERIMENT

The pneumatically operated extendible antenna mast, proposed for CTF use in the previous section, was erected out doors, and experiments were performed to determine and characterize its motion in windy conditions.

A description of the measured parameters is detailed in section 3.1. The apparatus and procedures used in this experiment are presented in sections 3.2 and 3.3 respectively.

3.1 MOTION OF TOWER IN WIND

a) Resonant Frequency of Tower

The resonant frequency of the tower was determined for fully erected and half erected tower positions.

b) Deflection of Tower in the Wind

The deflection characteristics of the tower were evaluated in the presence of a mock antenna. These deflection experiments yielded insight into the behaviour of the tower when used in conjunction with the real antenna.

c) Deflection of the Tower Under Given Loads

Using a guy wire a calibrated force was applied to the top of the tower. The applied loads were measured using a force gauge and the net deflection of the tower was determined with the help of a graduated scale mounted below the mock antenna. The deflection values read using a theodolite were compared with their theoretical counterparts. The results of this comparison yielded insight into the mechanical stability of the tower to enable the tracking system requirements to be defined.

d) Extension and Retraction Capabilities of the Tower

The time, effort and the equipment required to extend and contract the tower were evaluated. These data were intended to assist in the evaluation of the suitability of the apparatus for use in the "field" environment.

3.2 EQUIPMENT SETUP

The tower used in this experiment was a 15.25 m tall RACAL retractable mast. This mast consisted of several lengths of hollow tubing which, due to its telescopic design, enabled adjoining sections to collapse into one another thereby giving a retracted length of less than 3.36 m. Once extended, each section was held in place by clamped joints located along the length of the mast. This structure was mounted in a wooden brace structure as illustrated in Figure 3.1. Two 202.5 litre drums filled with water were placed on the platform to act as ballast. To simulate the actual operating environment as closely as possible a dummy antenna was fixed on top of the mast and a graduated scale was placed several centimetres below it. The dummy antenna was made of a .31 m by .31 m piece of rigid waterproofed cardboard. The 0.0929m^2 area was chosen as this was the anticipated size of the real antenna. An antenna representative of that to be used in conjunction with the proposed MLS system is illustrated in Figure 3.2 (refer to section 5.3 for further information on the antenna). The dummy antenna was used to observe the behaviour of the mast in wind when loaded with an object mechanically similar to the real antenna. A graduated scale enabled the deflection of the mast to be measured accurately under various load conditions.

Using an optical telescope the displacement of the mast was observed from an environmental enclosure located 15.25 m from the wooden platform. The crosshair of the telescope was aligned with the centre of the scale mounted on the antenna and deflection of the mast due to the application of each load was observed directly on the scale.

The telescope which was placed on a mount is capable of moving independently in both the azimuth and elevation axes. The telescope and mount are very similar to the type proposed for the tracking system outlined in section 4. The positioning of the mount was controlled by a computer resident in the environmental enclosure. The computer issued a set of instructions to a pair of indexes which in turn converted these signals into a series of pulses and applies them to two stepper motors located in each axis of the mount. The stepper motors move either or both axes of the mount a angular distance proportional to the number of pulses received.

Using the above set up the various characteristics of the mast were determined.

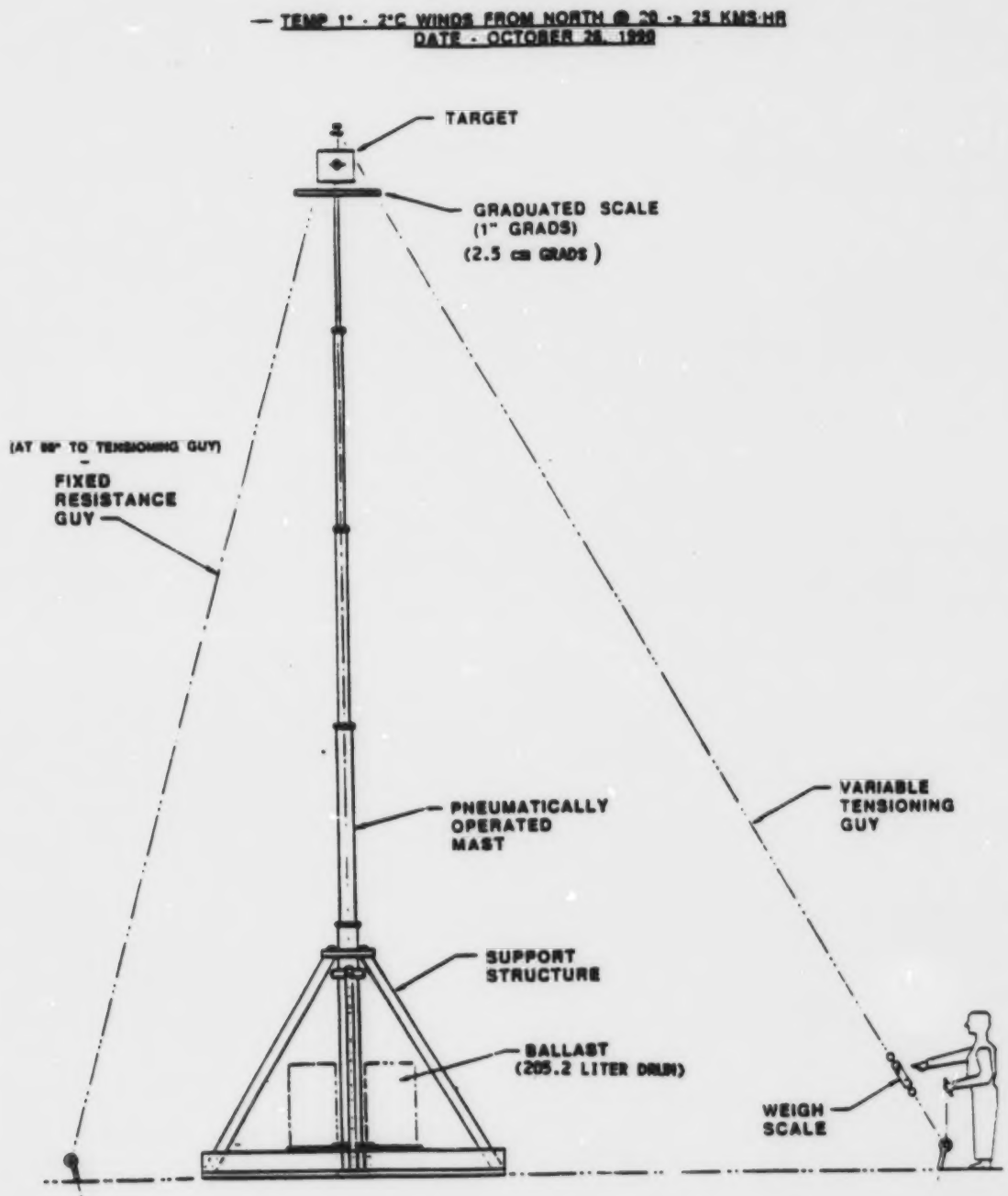


Figure 3.1 Experimental Mast

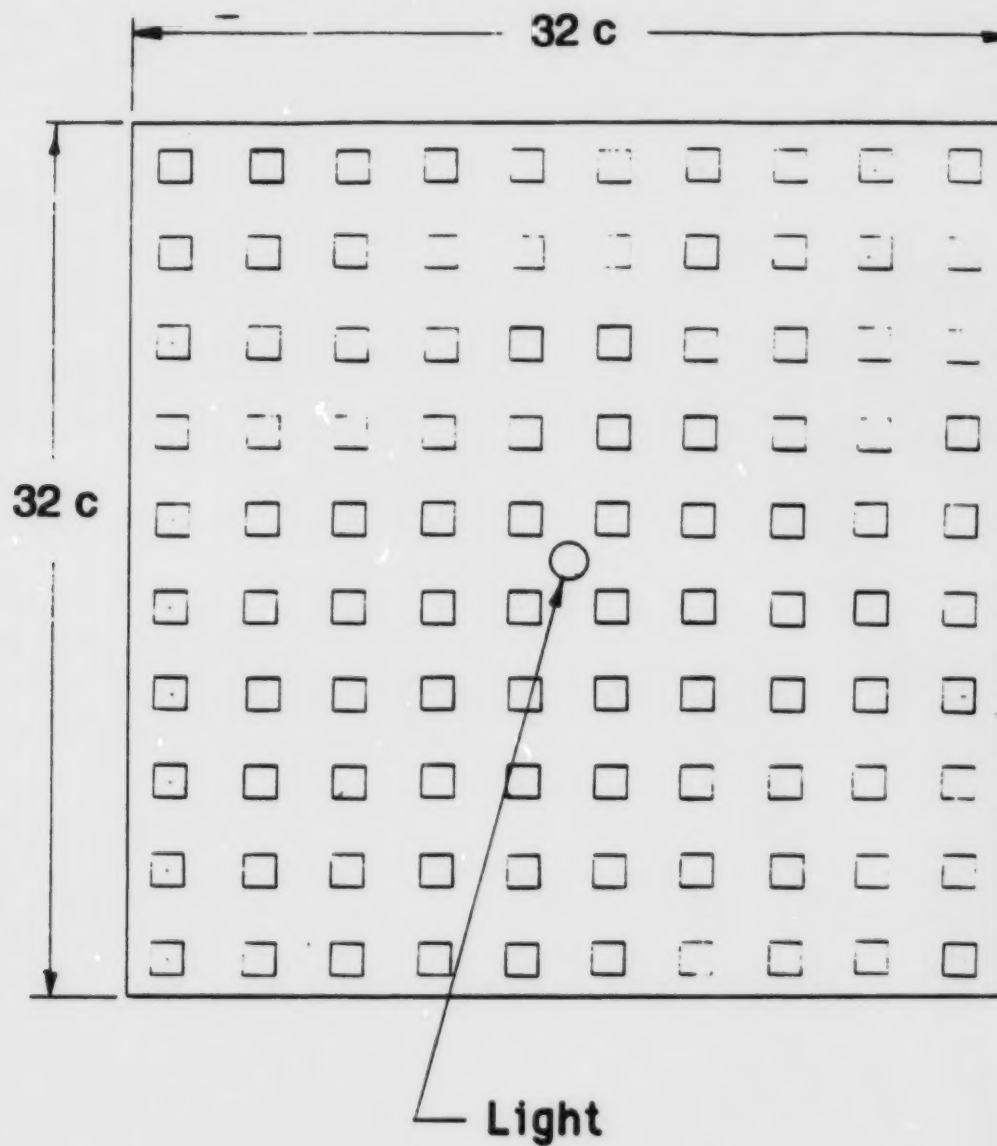


Figure 3.2 Antenna for the Proposed MLS System

3.3 PROCEDURE AND RESULTS

i) Motion of Tower in the Wind

a) Resonant Frequency of Tower

The mast was fully extended and then made to oscillate using a guy wire to give it a sharp lateral displacement to one side. Using the telescope in the environmental enclosure and a stop watch, the time taken to complete several oscillations was noted. From this information the resonant frequency of the fully extended mast was calculated a being 0.8 Hz. The same process was repeated with the mast half extended. In this case the resonant frequency was calculated to be 1.1 Hz.

b) Deflection of Tower in the Wind

The fully erected mast swayed $7.6 \text{ cm} \pm 1.25 \text{ cm}$ (measured using the procedure outlined in section 3.1C) in a $25 \pm 5 \text{ km/h}$ wind (obtained from the Meteorological Department located at the Ottawa International Airport). This displacement was greater than that predicted by theory. The reasons for this were determined to be the looseness in the joints, and also the overtravel due to gusts versus steady wind. To reduce this deflection the mast was tensioned using a fixed guy in one direction. The tensioned mast was seen to sway by 5.1 cm to 7.6 cm. A reduction to over half its untensioned counterpart.

c) Deflection of the Tower under a Given Load

Using a pretensioned guy wire calibrated forces of 2.25, 4.5 and 6.75 kg representative of loads expected in the field were applied to the top of the tensioned, fully extended mast. The deflection and the sway about that deflect undergone by the mast for each of the applied loads was noted. This process was repeated for the untensioned mast, the results for both these cases are presented in Tables II and III and plotted in Figure 3.3. From these results it is seen that the untensioned mast was displaced further than its tensioned counterpart for all applied loads. Thus, it is seen that tensioning provides a simple yet effective way in which the net displacement can be significantly reduced. Furthermore it was observed that the deflections undergone by both the tensioned and untensioned masts were greater than that predicted by theory. This discrepancy was found to be due to the looseness in the joint

mechanisms of the mast. Therefore it is proposed that the final design of the mast be built with joints which effectively reduce looseness in the fully erected state to further restrict its lateral motion.

d) Extension and Retraction Capabilities of the Tower

The mast was extended and retracted several times in order to test its operational complexity. It was noted that using a foot pump a two man team took about 2 minutes to extend the mast and about one minute retract it. The mast was seen to be both sturdy and rugged and proved to have the required mechanical strength and stability. Use of a compressed air system would negate the use of manual labour thereby considerably shortening the mast extension time.

Results

Resonant frequency of mast

Fully erected $((2.83 \pm 0.25)\text{sec}/2 \text{ oscillations})^{-1} = 0.8 \text{ Hz}$
Half erected $((2.03 \pm 0.25)\text{sec}/2 \text{ oscillations})^{-1} = 1.1 \text{ Hz}$

Table II - Mast Tensioned (with resistance guy)

Load (kg)	Deflection (cm)	Sway about Deflection (cm)
0	0	5.08
2.25	5.08	2.54
4.5	7.62	5.08
6.75	16.5	2.54

Table III - Mast Untensioned (without resistance guy)

Load (kg)	Deflection (cm)	Sway about deflection (cm)
0	0	7.62
2.25	20.32	2.54
4.5	38.10	2.54
6.75	44.45	5.08

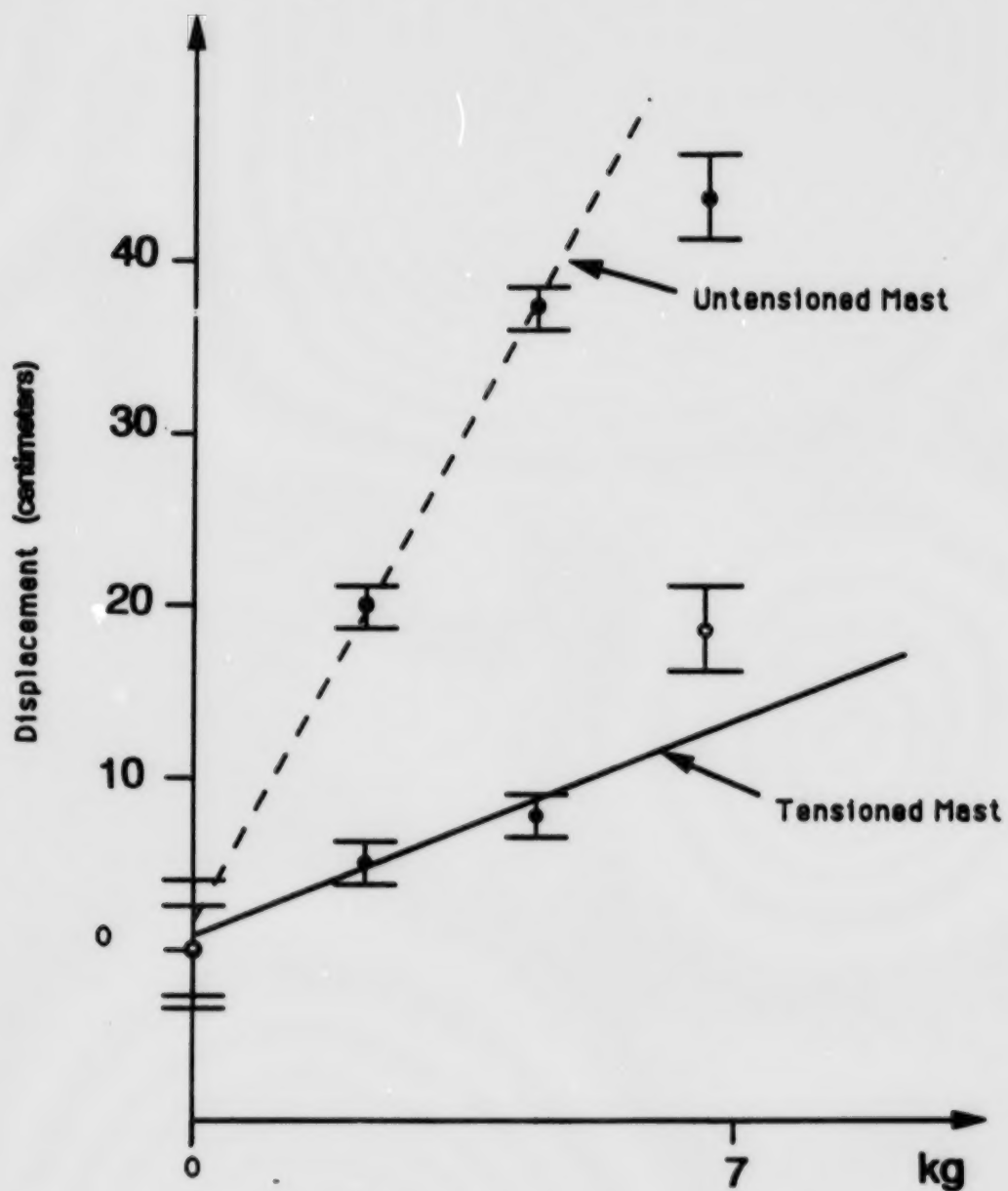


Figure 3.3 Deflection Results for the Experimental Mast

3.4 CONCLUSION

The experiments conducted on the mast in a practical environment indicate that the pneumatically extendable telescopic mast is capable of satisfying the MLS tower requirements when used in conjunction with an appropriate tracking system.

The representative mast used here exhibited deflections under load that were in excess of those expected on a theoretical basis. This deviation can be explained by the lack of rigidity displayed by the joint mechanisms that separate each section.

The mast can be stiffened considerably, and hence its deflection under load reduced, by implementing the following steps:

- Fewer Section in the Mast (the mast used for the test was longer than the required 15.25 m)
- Design of Joint Stiffeners
- Slight Tensioning of the Mast

The rigidity of the mast and the tracking system parameters would have to be traded off against each other to provide an optimum practical system.

On the basis of experimental measurements, this type of mast system, when fitted with joint stiffeners, slightly tensioned, and used with a tracking system, is capable of providing a technically sound solution to the MLS calibration antenna requirements, while providing the optimal operational convenience at the lowest cost.

4.0 TRACKING SYSTEM INVESTIGATION

4.1 REQUIREMENTS

The tracking system is intended to track the motions of the MLS probe antenna as the transmitted MLS signal is being measured and analyzed as illustrated schematically in Figure 4.1.1. The precise form of the tracking system depends on the nature of the motion that the probe antenna mast is expected to exhibit, and on the operational parameters of the system.

In this section, the requirements of the tracking system are specified, a number of basic types of tracking systems considered, and a preferred option selected. Furthermore, a conceptual design of a tracking system based on the preferred option is presented.

Certain tracking system peripheral issues are also addressed including, methods of telemetering the tracking system data to the remote MLS CTF processor, and a method of incorporating these data into the MLS signal analyzer.

The requirements for such a system are detailed below:

- i) The tracking system must define the position of the calibration antenna to an accuracy of $\pm 0.005^\circ$ (± 3 mm at a range of 40 mm) or less (i.e. within ± 18 arc sec)
- ii) The system must also be able to gather accurate position readouts of the Calibration antennae. The time uncertainty associated with these measurements should be maintained at an acceptable value, consistent with achieving the specified angular precision.
- iii) The system must be portable. Therefore weight and size are a critical factor.
- iv) The system must be remotely controllable. So that operator intervention can be kept to a minimum.

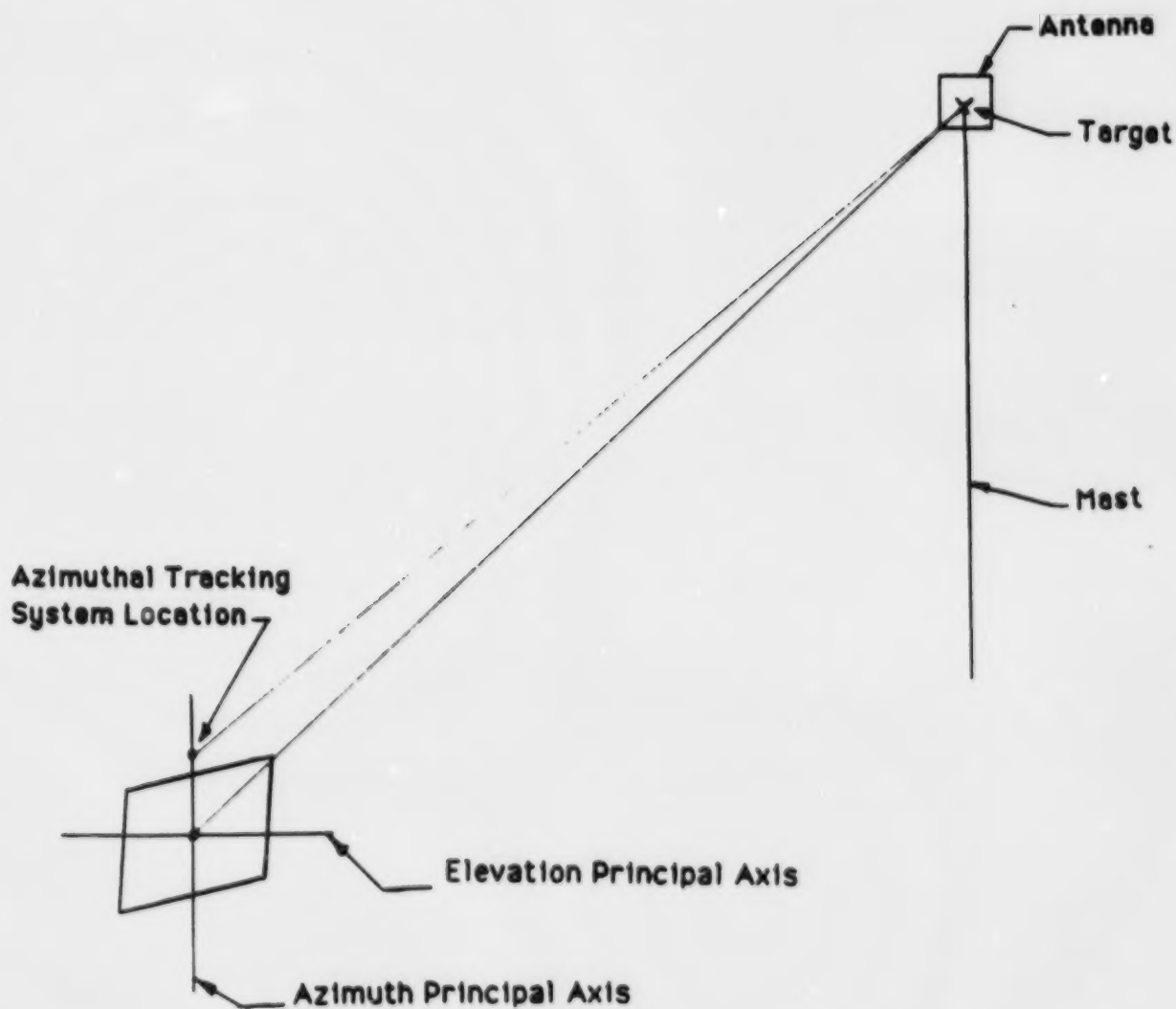


Figure 4.1.1 Tracking Probe

4.2 IMPLEMENTATION OPTIONS

Several options including radar, sonar, and various optical techniques were considered for implementing the proposed tracking system. Each of these options were evaluated, and are summarized in subsequent sections according to the following criteria:

- i) Error introduced by system
- ii) Operator interaction
- iii) Availability/amount of development required to obtain finished product.
- iv) Portability

The appropriate design encompassing the characteristics best suited for this tracking system was then selected.

The following text contains a brief description of each of the considered designs.

4.2.1 Ultrasonic Ranging System

This system is very similar to a sonar except that it operates in air rather than in water. It was chosen as a candidate for consideration because the velocity of propagation of sound waves in air is much slower than that of radar waves, and hence could potentially be more sensitive to small distance variations. This technique obtains range information by transmitting soundwaves of a known duration and measuring the two way transit time to the target. A superficial analysis would conclude that this system would have an accuracy similar to that of sonar, but as in the case of a water medium, the velocity of sound in air varies with the medium density and velocity. Therefore the error introduced by both these quantities, particularly rapid wind velocity changes (gusts), would have to be measured and taken into account when calculating the range to the target. The wind velocity sensors and the algorithms required to calculate these errors are quite complex and would prove to be rather difficult to implement. Another complicating factor associated with the use of this system is the phenomena of multiple reflections. Multiple reflections occur when the transmitted wavefront reflects off other objects in the vicinity of the target thereby making it extremely difficult to differentiate the desired return from the background clutter. As such products are not currently available on the commercial market the development of this system would require a vast amount of time and effort thereby making it economically unfeasible. Due to the aforementioned technological and economic uncertainties this system was omitted from the list of viable options.

4.2.2 Radar Ranging System

A pulsed radar was investigated for use in the proposed tracking system. Such a system obtains range information by transmitting an electromagnetic pulse of known duration and measuring the two way transit time to the target. The main drawback associated with this system is that in order to obtain the required ± 3 mm range resolution the duration of the electromagnetic pulse has to be less than 20 ps. With current technology it would be extremely difficult and relatively expensive to obtain pulse widths of this magnitude. It is also seen that the phenomena of multiple reflections which was explained in the previous section has similar adverse effects on radar ranging systems. Due to technological constraints imposed by the required pulse width and the problems anticipated with the multiple reflection phenomena this scenario was not considered any further.

4.2.3 Tracking Theodolite

Two types of theodolites, optical and microwave, were considered for the tracking system. The attractive feature of these systems was that they are commercially available and are extremely portable.

Optical Theodolite

The first type uses an infrared beam to sight on a glass prism mounted on top of the desired target. The prism reflects the infrared beam back to the theodolite which then performs the appropriate calculations to obtain the range to the target. These devices have range accuracies extending from several centimeters to $\pm .0002$ meters. The accuracy and ease of use exhibited by these systems have enabled them to obtain wide commercial acceptance in many fields of engineering. A typical system which uses the above mentioned measurement technique is the DTMA20 "total station" theodolite measurement system built by Nikon. The main flaw associated with these devices is their inability to provide range or angular information for objects off axis. Therefore in the case of a moving target an operator stationed at the tracking site would have to manually track the object to enable the system to have continued access to the object's positional offset. This would prove to be extremely cumbersome in the case of the calibration antenna which, under windy conditions is liable to oscillate with a period of about 1 Hz. These systems were excluded from the selection process as they require the use of an operator at the tracking site and their operation would prove to be extremely tedious when used to track the calibration antenna as described above.

Microwave Theodolite

The second type of device investigated for this system was a microwave theodolite. Most commercial devices which fall into this category were seen to have insufficient range accuracy. The most accurate microwave theodolite evaluated in this analysis was the "Polartrack" system built by Krupp Atlas Electronics. It has a range accuracy of ± 0.15 m and an angular accuracy of 0.006° . It also has the ability to track moving targets and is used in industry to evaluate certain aircraft parameters during flight trials.

Though these systems have many desirable performance characteristics, they all lack the desired range accuracy thereby making themselves unsuitable for use in the proposed system.

4.2.4 Optical Tracking System

This system consists of a remotely controllable tracking mount with a video camera mounted on it. The video camera is used to observe the deflection of the calibration antenna within its field of view, while the mount is used to position the camera to various points on the measuring grid. The camera lens forms a focused image of a light fixed to the calibration antenna on to a CCD array. The analogue output data of the CCD array are digitized using a framegrabber then processed to obtain the positional offset of the calibration antenna. For the proper operation of this system it is vital that the calibration antenna remain within the field of view of the camera. This enables the system to obtain periodic updates of the antennas position thereby eliminating the need for a continuous tracking system.

In principle, the precision of this type of tracking system depends on the selection of CCD array pixel size, and spacing, and on the selection of the focal length of the lens used to form the image of the object being tracked on to the CCD array. Practically, tolerances of the components of the system, such as the lens quality, and tracking mount angular read out devices also are a factor.

It is possible to select both CCD arrays and camera lens so that an angular resolution of 0.0025° set at one half of the overall system requirement, can be achieved.

4.3 PREFERRED TRACKING OPTION

The CCD array based optical tracker was selected for implementing the proposed system. The reasons for selecting this design over the others are stated below:

- i) The processing technique used in this design eliminates the need for continuous manual tracking of targets. This reduces the complexity of both the hardware and software associated with the design, and also reduces operational labour costs.
- ii) This system also offers a positional accuracy which is substantially greater than that available from any other commercially procurable product over the required measurement area.
- iii) This design does not impose any foreseen major technological barriers, and the subcomponents required to build this system are all commercially available. Therefore the development time and risk required to obtain a finished product is minimized relative to the other options considered.
- iv) This system does not contain excessive hardware, therefore it can be designed to be portable.

This option represents a simple yet versatile design which is capable of meeting all the requirements demanded of the proposed tracking system, with a minimum of development risk.

4.4 TRACKING SYSTEM CONCEPTUAL DESIGN

The proposed tracking system illustrated in Figure 4.4.1 consists of a video camera mounted on a tracking mount along with the associated hardware and mechanical structures.

The calibration antenna measures the signals emitted by the MLS phased array antenna under test and conveys these readings to the MLS CTF processor. The geometry of the tracking system with respect to the MLS probe 2 antenna is shown schematically in Figure 4.1.1. As the beam pointing angle of the phased array has to be determined to a relatively high degree of precision, the unavoidable deflections of the calibration antenna during the RF measurement process have to be known. The proposed tracking system must provide a means by which this deflection can be measured. The geometry, as depicted in Figure 4.1.1, is selected such that the angular coordinates measured with respect to the principal axis are those measured directly, without need for geometrical correction. Here, the principal axis refers to that axis about which the precision

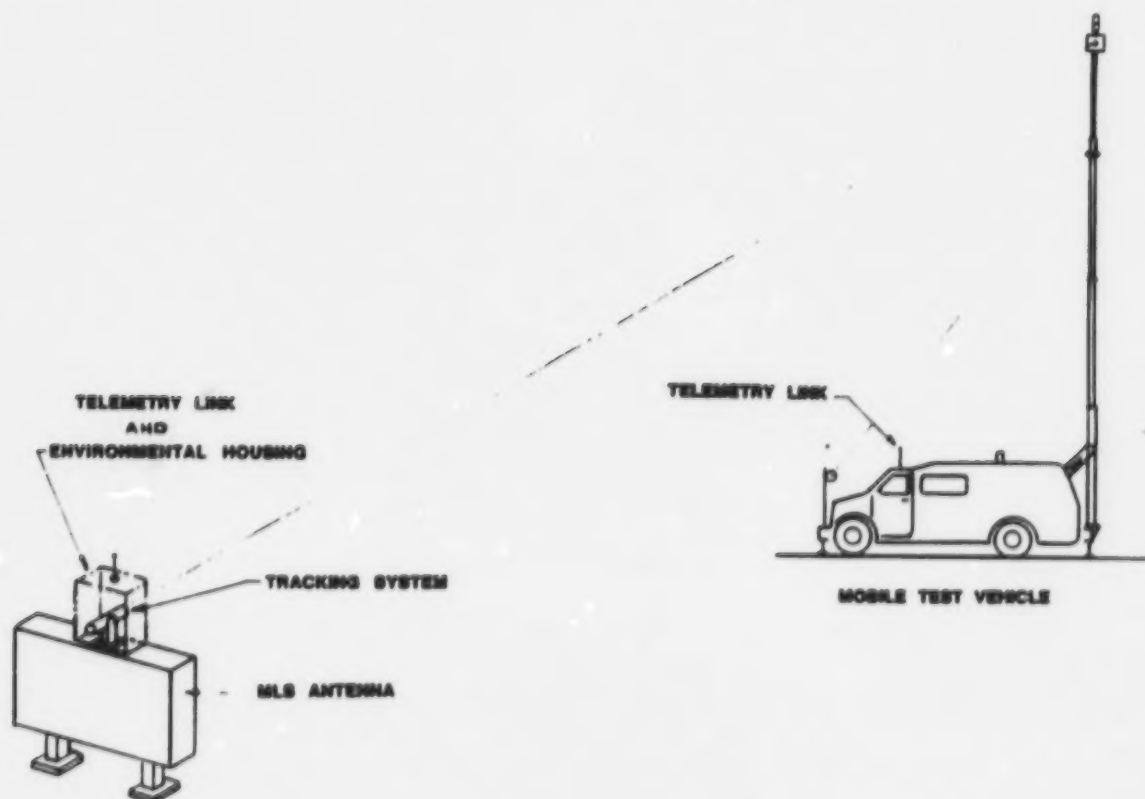


Figure 4.4.1 Conceptual Design of Tracking System

measurements are required. Precision angular measurements are only ever required for one axis at a time with this system.

By way of example, in the case of azimuthal measurements, the principal axis points in the vertical direction, and passes through the centre of the MLS transmitting antenna.

Consequently, the Azimuthal tracking system would have to be located either on the top centre, or bottom-centre of the Azimuth antenna. Similarly for the elevational tracking system, where the principal axis points in the horizontal direction, the elevation tracking system would have to be mounted on either the left-or right-centre of the elevation antenna. It is about this axis that precision angular measurements have to be taken.

The camera in conjunction with the framegrabber measures the deflection of the calibration antenna within it's field of view, while the tracking mount positions the camera to all predefined locations on the measuring grid. The movement of the tracker is controlled from the truck via a telemetry link. (This link also serves several other functions as outlined below). The output of the camera is digitized using a framegrabber and then processed by a CPU located either at the tracking mount or in the truck next to the MLS processor. The tracking system and its associated hardware will be housed in an environmental enclosure in order to protect it from the elements. The MLS CTF processor uses the data obtained from the tracking system in conjunction with that obtained from the calibration antenna to calculate the beam pointing accuracy of the antenna undertest.

The major components and some of the trade off analysis supporting its configuration are indicated below:

4.4.1 Tracking Mount

The video camera used to observe the movement of the calibration antenna will be housed on this mount. The pan and tilt mechanism of the mount enables it to move the camera independently about both the azimuth and elevation axes. Each axis of the mount can be moved to within ± 5 or ± 10 arc sec of the required position depending on the model of encoder that is used. Encoders mounted on each axis indicate the orientation of the tracking mount. Different types of encoders, having varying degrees of accuracy are currently available on the commercial market. To remain within the system error budget, only those devices having encoder errors of less than 5.0 arc sec will be considered.

4.4.2 Video Camera, Framegrabber

The video camera proposed for use in this system is a Sony XC77. It is a monochrome, NTSC compatible model with a

Pixel count of 768(H)X493(V). For each pixel to subtend an angle of 0.0025° the horizontal and vertical fields of view (which are then determined by the number of pixels) have to be limited to angular extents of 1.92° and 1.23° respectively. Given that the pixel dimensions of this CCD array are 11 by 13 μm , a lens having a focal length 250 mm, or larger, would yield the desired angular resolution of 0.0025°. To achieve these narrow fields of view a lens such as the 180 mm Cosmocar lens with an X2 extender could be fixed to the front of the video camera. The lens has a FSTOP of F1.9 and the use of the X2 extender would increase this value to F2.7. The low FSTOP guarantees the preservation of the contrast on the video images which is essential for the accurate processing of data. The analogue video output from the camera could be digitized using a PC Vision Plus frame grabber built by Imaging Technology Corporation. This model has a 512 x 512 pixel resolution and operates at a maximum speed of 30 frames/sec. To protect the video camera, tracking mount and PC from the elements this equipment (along with the accompanying hardware) must be placed in a environmentally protected enclosure.

A possible option that came to our attention after the submission of the final draft report was an electro optical displacement transducer. An electro optical displacement transducer could be used in place of the Sony video camera/framegrabber combination to characterize the motion of the calibration antenna. A preliminary investigation conducted into the Model 200 Electro Optical Transducer built by Zimmer Ohg indicates its suitability for use in this system. This device has the required system accuracy and its lightweight, portable packaging makes it suitable for use in an outdoors environment. The use of this transducer in the proposed tracking system would depend upon several factors such as: cost, availability, reliability and ease of use. It is recommended that this device be studied further, to properly assess its performance and suitability, prior to its inclusion as a viable option in the proposed tracking system.

4.4.3 Telemetry Link

The telemetry link between the MLS system and the tracking mount could be implemented as a full duplex link using two modems, such as the SLR96 modems built by Repco Incorporated. Each of the modem operates at a speed of 9600 bps, is RS 232C compatible and has a minimum operational range of 1.6 km. A block diagram of this system is illustrated in Figure 4.4.2. Each transmitter/receiver unit will be separated by a frequency offset of 5 MHz. The exact operating frequencies selected for each unit will depend upon the output power of the TX and the frequency bands currently available in and around the MLS operating environment.

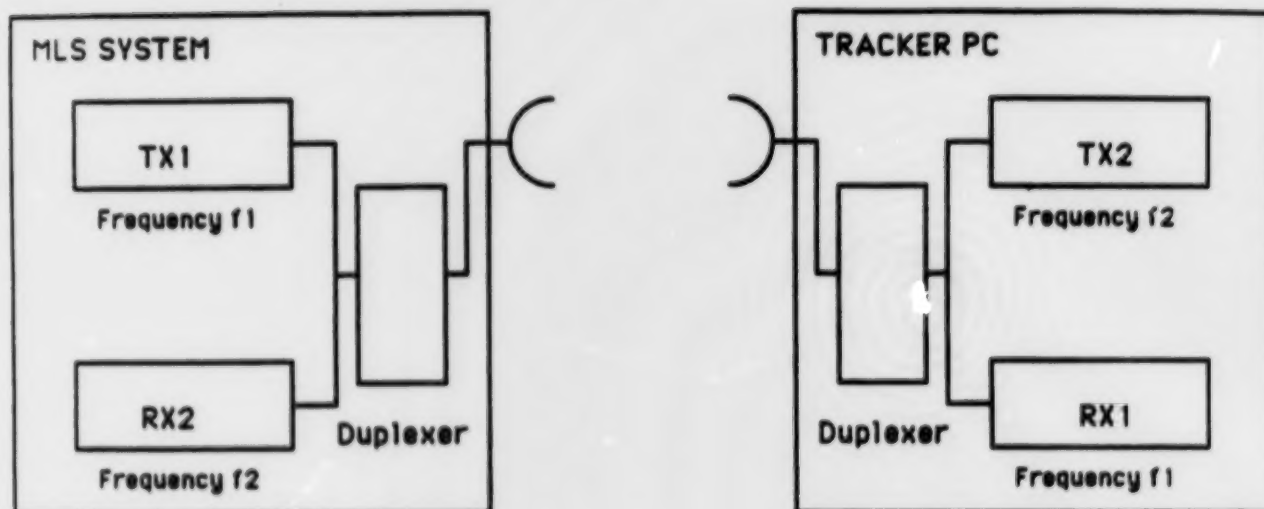


Figure 4.4.2 Conceptual diagram of telemetry link

Several types of antenna are commercially available for use with this type of system. Choices range from 1/4 wave monopoles with little or no gain to 5/8 wave antenna with 3 to 5 dB of gain. The antenna proposed for this system are two 0 dB 1/4 wave monopoles.

4.4.4 Hardware Configuration Analysis

The Tracking System can be constructed from the following building blocks, or sub-systems:

- i) Video camera & Lens
- ii) Framegrabber
- iii) CPU
- iv) Telemetry Link.

Depending on a number of factors, including the data transfer rates required of the telemetry link, the volume and rate of

processing performed at the remote site and on other system features selected by the user, the Tracking System hardware can be configured in several different ways. Two practical options were analyzed and outlined below. These two proposed systems differ primarily by the depth of processing performed by the processors located near the optical system, and the resultant requirements placed on the telemetry system.

Option 1)

In this scenario the framegrabber is installed in an environmentally controlled enclosure along with the tracker and video camera. The camera installed on the tracking mount has a physical link connecting it to the frame grabber. The framegrabber digitizes the analogue output from the camera and places the data in a local computer, such as a PC. Whenever the tracking mount is moved to a new location the PC checks several images for the presence of targets other than the calibration antenna. If a false target is detected the operator is notified of this by means of an error message. If no errors are detected and the operator wishes to continue sampling images the PC reads the sampled data and processes it to obtain the position of the calibration antenna at the sampling instants of time. These results are time tagged and stored in a circular buffer. When the MLS signal analyzer located in the CTF van requires a sample it sends a request to the PC. The PC time tags these requests and stores them in another buffer. When the sampling process is terminated the PC then performs an interpolation routine to determine the position of the calibration antenna at the time instants requested by the MLS. Once these values are calculated they are sent to the MLS processor via the telemetry link. When the system is configured in this manner the telemetry link would serve the following functions:

- i) Conveys results from the tracker PC to the MLS processor;
- ii) Notifies the operator of any potential tracking errors;
- iii) Allows the operator to control the position of the tracker in the azimuth elevation axes.
- iv) Enables the MLS Processor to send data requests to the tracker PC.

Option 2)

In this option only the tracking mount, the camera and one half of the telemetry link are placed in the enclosure while the PC, the framegrabber, and the rest of the telemetry link are located in the truck. A video link transmits the modulated analogue output of the video camera to a receiver located in the truck. The signal received at the truck is demodulated, and the sampled by means of a framegrabber. The sampled data is then input to a PC where it is processed to obtain the desired results. The video signal received at the truck can also be input to a display terminal thereby allowing the operator to view the video image observed by the camera. This feature proves to be most useful when positioning the camera to the predefined locations on the measuring grid. It also enables the operator to visually verify in real time the presence of multiple targets that may appear in the field of view. The presence of this link enables the video data to be transferred from the remote site to the PC located in the truck. This in effect eliminates the need for complex processing at the remote site, but significantly increases the data transfer rate required of the combined telemetry and video RF link.

The quality of the images received over this link are highly dependent upon the relative positions of the transmit and receive antenna. For the proper functioning of a video link it is necessary to have the highly directive RX antenna pointed very accurately at its TX counterpart also, the two antenna have to maintain line of sight during the data transmit periods (If these criteria cannot be satisfied then the quality of the received images would suffer). As mentioned before the position of the truck changes over the course of the measurement period. This means that the position of the RX antenna would have to be constantly altered to compensate for the change in the aspect angle between the TX and RX antenna. If this compensation were to be performed automatically then additional hardware would have to be incorporated into the existing design to accommodate this feature.

When the hardware is configured for this option the telemetry link would only be used to control the position of the tracker about its azimuth and elevational axes.

The PC proposed for this system is a IBM 386 or clone. The processing capabilities of this machine are likely to exceed the processing requirements of the tracking system, and would allow for future growth of the system. The precise processor requirements would have to be fixed.

4.4.5 Error Budget

The tracking error associated with this system can be divided into three categories, they are outlined below:

i) Mechanical errors:

These include all errors incurred by the mechanical components associated with the system, primarily the encoder and tracking mount errors.

ii) Optical error:

This error is related to the optical properties of the system. Assuming that the F stop of the lens is small enough that the system is not defraction limited, the main contributor to this error is the limit on resolution imposed by the finite size of the CCD array pixels. This introduces an uncertainty corresponding to approximately $1/2$ of the pixel dimension to measurements made at the focal plane. The resolution of the optical CCO arrays are discussed briefly in Appendix A3.

iii) Processing Error:

This error accounts for all uncertainty introduced by the processing mechanisms of the system. They include the time uncertainties inherent to the hardware/software interfaces as well as those time uncertainties associated with the telemetry link. These time uncertainties are summed, and then by taking into account the movement of the extendible mast are converted to a worst case angular value.

As each of these errors can be treated as being statistically independent the total error is calculated as being the square root of the sum of the squares of each individual component.

Error budgets for two representative systems are given below:

In the first case, commercially available optical encoders and tracking mounts having sufficient precision to achieve the total system error were selected. In the second case, higher precision optical encoders and custom built tracking mounts were selected, and the overall system precision requirements were exceeded.

In both cases, it was assumed that the combined CCD pixel size and lens focal length are selected such that one

pixel subtends one half of the maximum allowable system angular error. The processing error was also set to one half of the maximum allowable system angular error.

System 1)

The error RMS budget for this system which utilizes commercially available optical encoders and tracking mounts is given below:

Allowable error	=	$\pm 0.005^\circ = \pm 18$ arc sec
Encoder error	=	± 5.0 arc sec
Tracking mount error	=	± 10 arc sec
Pixel error	=	$\pm 0.0025^\circ = \pm 9$ arc sec
Processing error	=	$\pm 0.0025^\circ = \pm 9$ arc sec
Quadrature addition	=	$\sqrt{5^2 + 10^2 + 9^2 + 9^2}$ arc sec
<u>Total Error</u>	=	$\pm 0.0047^\circ = 17$ arc sec

System 2)

The error RMS budget for this system which utilized custom optical encoders and tracking mounts is as follows:

Allowable error	=	$\pm 0.005^\circ = \pm 18$ arc sec
Encoder error	=	± 1.0 arc sec
Tracking mount error	=	± 5 arc sec
Pixel error	=	$\pm 0.00025^\circ = \pm 9$ arc sec
Processing error	=	$\pm 0.00025^\circ = \pm 9$ arc sec
Quadrature addition	=	$\sqrt{1^2 + 5^2 + 9^2 + 9^2} = 14$ arc sec
<u>Total Error</u>	=	$\pm 0.0039^\circ = 14$ arc sec

Although the required system error tolerances can be achieved using customized optical encoders and tracking mounts, the use of custom built components would provide an additional margin of safety.

In addition, the component of the error introduced by the tracking mount (5 to 10 arc-sec) could likely be reduced by the implementation of appropriate alignment calibration

procedures.

It is also likely that the effect of the angular pixel size, and the processing error have been over weighted in the above error analysis. Most likely a well designed centre fitting algorithm could reduce the error of the position determination of the tracking light image on the CCD array to the order of one half pixel. This would reduce the combined processing and pixel error from that stated earlier ($\sqrt{9^2 + 9^2}$ arc sec) to the order of 5 arc sec.

4.4.6 Systematic Error Reduction

Certain safeguards will be implemented to prevent the tracking errors caused from observing spurious objects in the vicinity of the calibration antenna. These include mounting a coloured light on the calibration antenna and placing the corresponding coloured light filter in front of the video camera. This will force the tracker to only detect light sources of the selected colour, thereby greatly reducing the chance of the tracker reacting to spurious objects within the video image. More investigation into matched light sources and filters is required.

Whenever the camera detects more than one viable target in the vicinity of the calibration antenna, an error detection scheme implemented in software will notify the operator of the potential for erroneous tracking. At this point the operator would either move the tracker to a new position or terminate the tracking process until the ambiguity is resolved.

4.4.7 Conclusion

A suitable list of hardware associated with the proposed design is summarized in Table IV. This list is representative of the type of components that could be used in the tracking system. Any of these items can be substituted by similar components which perform analogue functions.

**Table IV - A Representative List of Components
for the Proposed Tracking System**

ITEM	MANUFACTURER	SPECIFICATIONS	DESCRIPTION
Mount	Questar	accuracies of ± 5 or ± 10 arc sec	Independent movement in both the azimuthal and elevational planes
Encoders	Questar	accuracies of 3.5 or 5 arc sec	-
Camera	Sony	XC77	768 x 493 pixel resolution
Lens	Comstar	180 mm with x2 ext.	-
Framegrabbers	PC Vision Plus	-	512 x 512 frame grabber
Telemetry Link	Repro	SLR 96	band rate of 9600
Hardware orientation and Processor selection	IBM 386 Option #1 or Option #2	-	-

A system comprising the aforementioned conceptual design and components similar to those outlined in Table IV would yield a versatile, cost effective design which would satisfy the demands of the proposed tracking system. Under the hardware configuration options described in section 4.4.4, it is likely that the benefits incurred by the adoption of option 2), in which the raw video information is transmitted to the CTF van for processing, would be far outweighed by the increase in complexity and cost that such a design would impose. Though this entails placing less hardware at the remote enclosure, the marginal utility gained by this feature is greatly exceeded by the increase in hardware costs that would have to be incurred for the implementation of the high bandwidth video link.

Therefore we are of the opinion that option 1), which entails placing the PC at the remote site, represents the desired balance between cost, complexity and user desirability. Hence we propose that the tracking system be implemented with the hardware orientation outlined in the latter case.

4.5 MLS SIGNAL ANALYZER INTERFACE CONCEPTUAL DESIGN

4.5.1 Processing and Interpolation of the Video Data

This system consists of two main processing operations. Process I deals with the detection of erroneous target images. It also handles the centring of the antenna within the field of view of the video camera. Process II is activated by the initiation of the periodic data gathering phase. During this phase it processes the periodically sampled video images and stores the pertinent results in a buffer. Upon completion of this phase it initiates an interpolation routine that determines the position of the target for times other than

those corresponding to the periodic sampling instants. A more detailed description of these processes is outlined below:

i) Process I - Detection of Erroneous Targets and Antenna Positioning

When the tracking mount is moved to a new location several video images are sampled to determine the presence of multiple targets. Each video frame is scanned either horizontally or vertically and the operator is informed of multiple targets in the form of an error message. The light mounted on the calibration antenna may be switched on or off between successive frames to enable the system to differentiate between the antenna and other targets that may be present on the video image. If the antenna is absent from the image then the operator will be informed of this, and a search routine is activated to locate the antenna. Once the antenna is located the video image is checked one last time to determine the presence of multiple targets. If no other targets are present the antenna is correctly centred with respect to the video image and then the periodic data sampling process (i.e. Process II) is initiated at the request of FAMAT. However, if other targets are detected the operator is again informed of this and further processing is terminated until the ambiguity is resolved or the tracker is moved to a new location.

ii) Process II - Tracking Image Processing

Process II involves the manipulation of video images obtained during the periodic data gathering interval. The movement of the calibration antenna during the picture integration period creates a banding pattern on the video images which complicates the subsequent processing. Fortunately the motion of calibration antenna is slow enough that a linear interpolation routine can be used to determine its position at the required time instants. A typical digitized image of the calibration antenna as seen through the video camera is illustrated in Figure 4.5.1. When the illumination is plotted as a function of position the graph illustrated in Figure 4.5.2 is obtained. If V_1 is the maximum illumination then the position of the calibration antenna at the beginning and end of the integration period is defined as those positions corresponding to illumination levels of $0.1 V_1$. Therefore in the 2K buffer the position values X_1 , and X_2 will be stored along with the corresponding time stamp X_t . The data in this buffer would have the format depicted in Table V.

Table V - Time and Position Characterisation of Video Images

Video Image	X_1	X_2	Xt
1	$X_{1,1}$	$X_{1,2}$	$1t$
2	$X_{2,1}$	$X_{2,2}$	$2t$
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
N	$X_{N,1}$	$X_{N,2}$	Nt

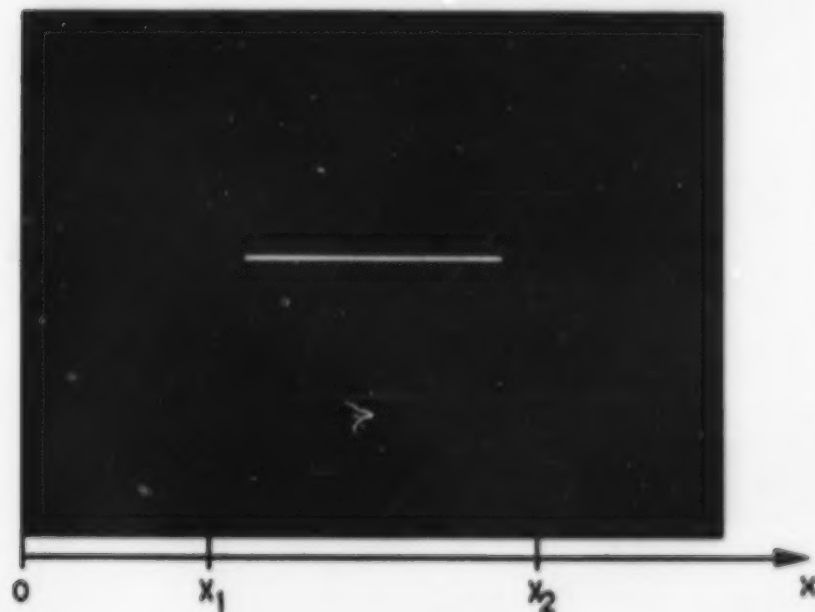


Figure 4.5.1 Typical video image

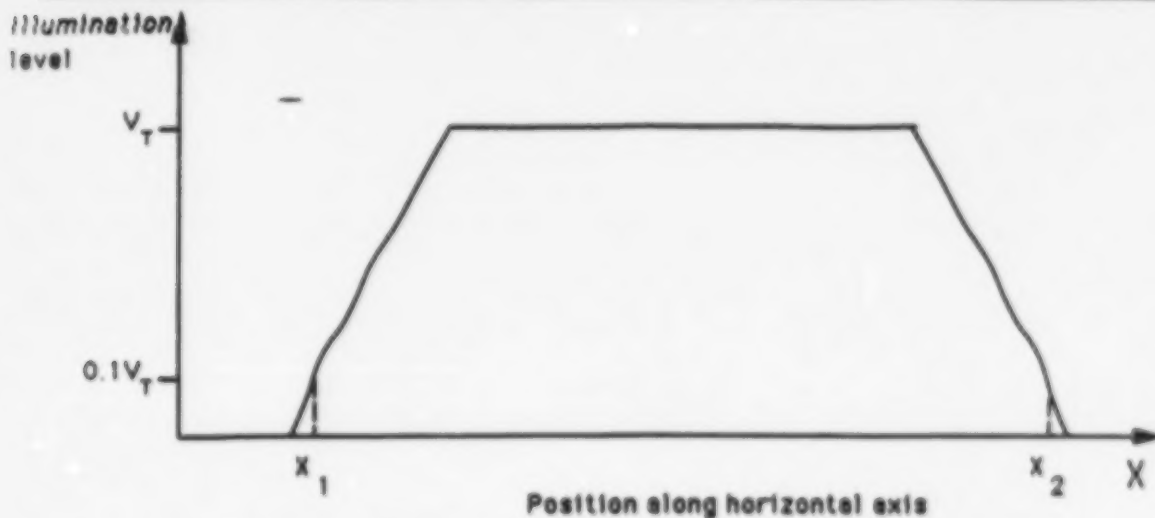


Figure 4.5.2 Illumination pattern for a typical video image

The number of video images processed per second bears a one to one correspondence to the 30 frame/sec sampling frequency of the video frame grabber. Though consecutive values of X_1 and X_2 may be disjoint the antennas direction of travel can be easily determined by examining several consecutive entries in Table V. During the processing of video data the DATA REQs issued by FAMAT have to be time stamped and stored in another buffer. Table VI outlines the format of this buffer.

Table VI - Data Request Buffer

Data request#	Time stamp
1	1.41 t
2	2.32 t
.	.
.	.
.	.
N	10.06 t

Using the data illustrated in Table V the position versus time function for the calibration antenna can be easily determined. This function, illustrated in Figure 4.5.3 presents the position of the antenna at the instances when each video frame was digitized. Providing the direction of travel of the mast does not reverse in between samples, the position of the antenna at the digitizing instants would be either X_1 or X_2 depending on whether the antenna was moving left or right, respectively. The case in which the antenna mast reverses direction in between samples must be considered separately.



Figure 4.5.3 Position versus time function for the calibration antenna

To determine the position of the antenna at the time instants requested by FAMAT the appropriate data such as that presented in Table V must be interpolated using a suitable algorithm. There are a large number of classes of algorithms that can be used to interpolate the angular data. One such technique that is capable of satisfying the system requirements is discussed below for completeness.

Interpolation Routine

For ease of exposition, the position versus time curve presented in Figure 4.5.2 is redrawn as illustrated in Figure 4.5.4.

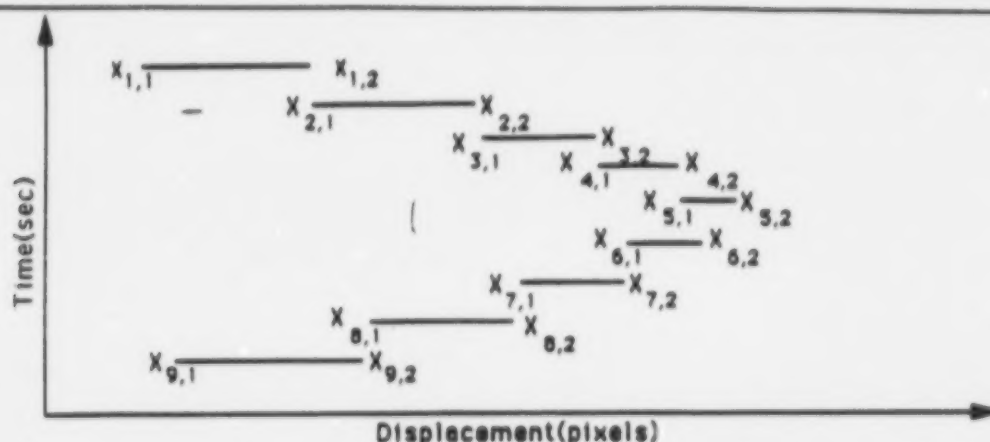


Figure 4.5.4 Movement of the calibration antenna

From Figure 4.5.4 it is clear that between time intervals 1 through 4 the antenna is moving right, and during intervals 6 through 9 it is moving left. T5 represents the interval during which the antenna changes direction from right to left. The methodology adopted in this analysis is outlined below:

i) Determine the direction of motion of the calibration antenna

This can be done by checking consecutive time intervals as follows:

- 1) If the object is moving right then it should be orientated such that

$$X_{i+1,2} > X_{i,2} \quad (1)$$

- 2) while objects moving left should adhere to

$$X_{i+1,1} < X_{i,1} \quad (2)$$

Using these two equations the direction of movement during certain time intervals can be determined.

ii) Determine the intervals during which the antenna changes direction

When the antenna is moving right these intervals will be those with the largest $X_{i,2}$ displacements. When the antenna moves left these intervals will correspond to the most negative $X_{i,1}$ positions.

iii) Determine velocity curve

The intervals determined in the previous section are discarded and the velocity at each of the remaining intervals are calculated using the equation given below:

If moving right:

$$V_i = \frac{X_{i,2} - X_{i-1,2}}{\Delta t} \quad i-1 \leq t < i$$

If moving left:

$\Delta t = 1/30 \text{ sec}$

$$V_i = \frac{X_{i,1} - X_{i-1,1}}{\Delta t} \quad i-1 \leq t < i$$

If these points are plotted the curve illustrated in Figure 4.5.5 would be obtained.

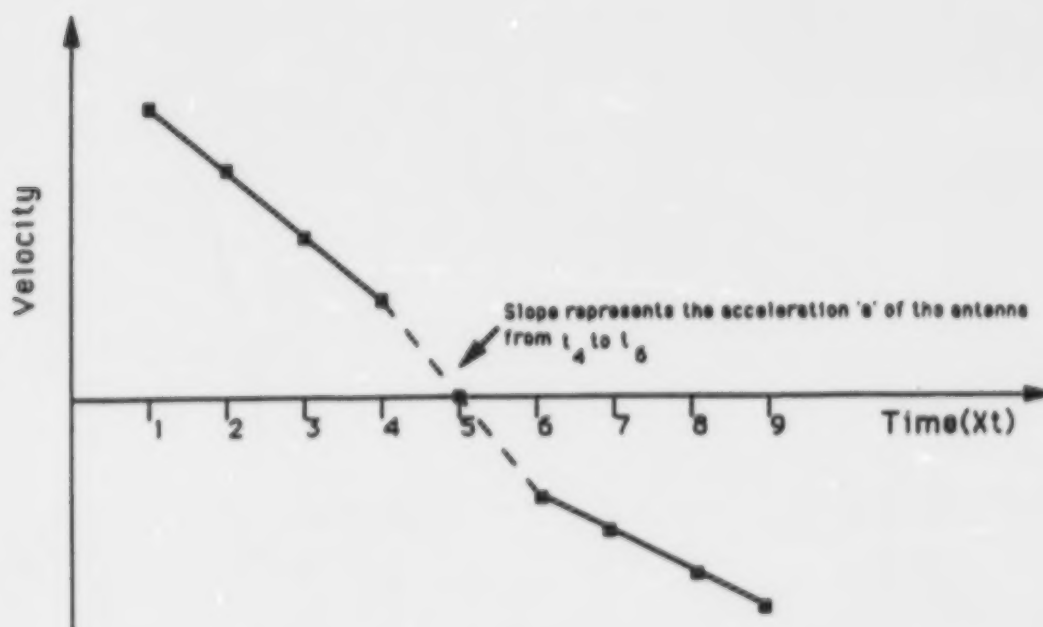


Figure 4.5.5 Velocity versus time function for the calibration antenna

The velocity points between pts 4 and 6 will be interpolated using these velocities as the end pts. This part of the velocity curve is represented by a dashed line in the above figure.

The position of the calibration antenna at the requested instances can now be determined by linearly interpolating between the X_{1N} and X_{2N} intervals whose digitizing instances are located on either side of these requests. The equation used to determine the instantaneous position would depend on the direction of movement of the calibration antenna.

If a particular time request falls into an interval when the antenna is moving right then the instantaneous position could be calculated using the following equation:

$$X_{jt} = \frac{X_{i,2} - X_{i-1,2}}{\Delta t} \times (jt - t_{i-1}) + X_{i-1,2}$$

Where jt is the time stamp associated with a particular request which falls in between the $i-1$ and i digitizing instants.

If the request falls into an interval when the antenna is moving left then the equation to be used is:

$$X_{jt} = \frac{X_{i,1} - X_{i-1,1}}{\Delta t} \times (jt - t_{i-1}) + X_{i-1,1}$$

Finally if the request falls into a region where the antenna is changing direction then the required position can be calculated using the following equation:

For objects moving right:

$$X_{jt} = V_i(jt - t_i) - 1/2a(jt - t_i)^2 + X_{i,2}$$

For objects moving left:

$$X_{jt} = V_i(jt - t_i) - 1/2a(jt - t_i)^2 + x_{i,1}$$

Where the quantity 'a' is illustrated in Figure 4.5.5, and V is the velocity of the antenna in the interval prior to that in which the antenna changes direction.

Tests conducted on the extendible mast have revealed that during the sampling interval in which the antenna changes direction, its positional displacement is altered by less than one pixel width. Therefore the error incurred by neglecting the change in direction during the corresponding sampling interval is insignificant. This means that the aforementioned velocity curve need not be calculated and the position of the antenna during that time interval is assumed to be restricted to a particular pixel offset.

4.5.2 Comparison of the Current and Upgraded Software Architectures

In order to interface the tracking system with the current MLS Signal Analyzer design, a thorough understanding of the existing software structure is required. To achieve this end the following section will first outline the main software architecture of the MLS Signal Analyzer. It will then proceed to describe the conceptual design changes that are proposed to be implemented to accommodate the new tracking system.

Figure 4.5.6 illustrates the different tasks associated with the current MLS system. The software associated with this system is divided into two independent, concurrent modules which are responsible for performing the following tasks:

- i) Sampling of the antenna power pattern. (FAMAT task)
- ii) Reading the encoder interface angle. (Turn task)

The main software module in the MLS system is the FAMAT routine. It is responsible for performing the following detailed tasks:

- i) Capture of the transmitted antenna signal pattern;
- ii) Calculation of the beam centre and the dynamic sidelobe levels.
- iii) Input and Output of all data/results to and from the system.
- iv) Generation of the beam pattern for antenna system test purposes.
- v) Initialization of mailboxes and execution of main the program.

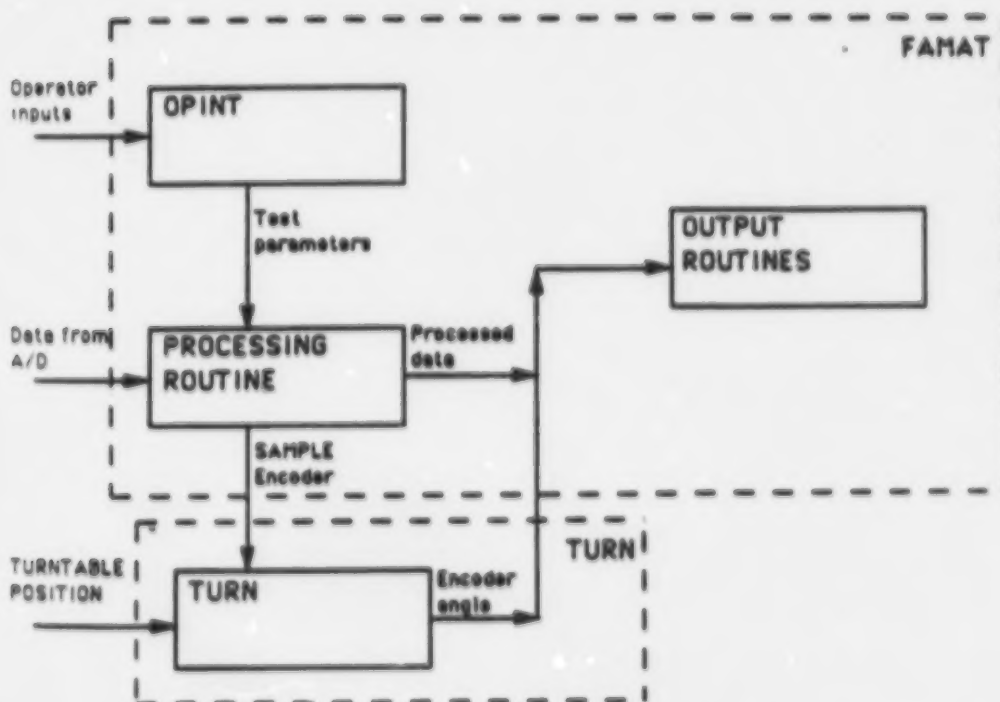


Figure 4.5.6 Current software architecture

The secondary module in this system is the TURN routine. The function of this routine is to read the turntable encoder angles. These values are input through a RS232C port located on the front panel of the MLS unit. This task is activated when the run command (GO.CP) is executed. Once activated all the signals (semaphores) required to operate this routine are created.

The instructions and data passed between the FAMAT, TASK and the turntable encoder are illustrated in Figure 4.5.7. FAMAT instructs TURN to read an angle from the encoder by using the semaphore GETM. When this semaphore is received by TURN it instructs one of its submodules READENC to read the encoder position. The obtained value is then converted to a number in the range -180° to $+180^{\circ}$. This value is then displayed on the console and stored in a buffer. When a predetermined number of position values have been gathered, TURN waits for the semaphore SEND. Once TURN receives this semaphore it sends all values in the mail to FAMAT.

The signal/data diagram for the mobile MLS system is illustrated in Figure 4.5.8. When defining this diagram every effort was made to preserve the existing software architecture. This approach was adopted in order to minimize the effect of integrating the new software code into the existing design.

FAMAT initiates the data sampling process by sending the START semaphore to the task NEW. NEW in turn instructs the PC to begin sampling data. The video data is sampled periodically at a rate of 30 frames/sec. The sampled video frames are processed by the PC and the results are time tagged and stored in a 2 Kbyte buffer. Each video frame is processed into 5 bytes of information. Four bytes are allocated for data while the fifth byte is reserved for the time stamp. As 30 frames are gathered every second the 2 Kbyte buffer would be completely filled within 13 seconds. Therefore to prevent this size of buffer from overflowing the data gathering period should be restricted to 13 seconds or less. When FAMAT requires a positional update of the calibration antenna it sends the GETM semaphore to task NEW. NEW responds to this command by sending a DATA REQ to the PC. The PC then time tags this request and stores it in a buffer. In all, up to 32 such updates could be requested by FAMAT. FAMAT concludes the data gathering process by issuing a TERMINATE command to the PC.

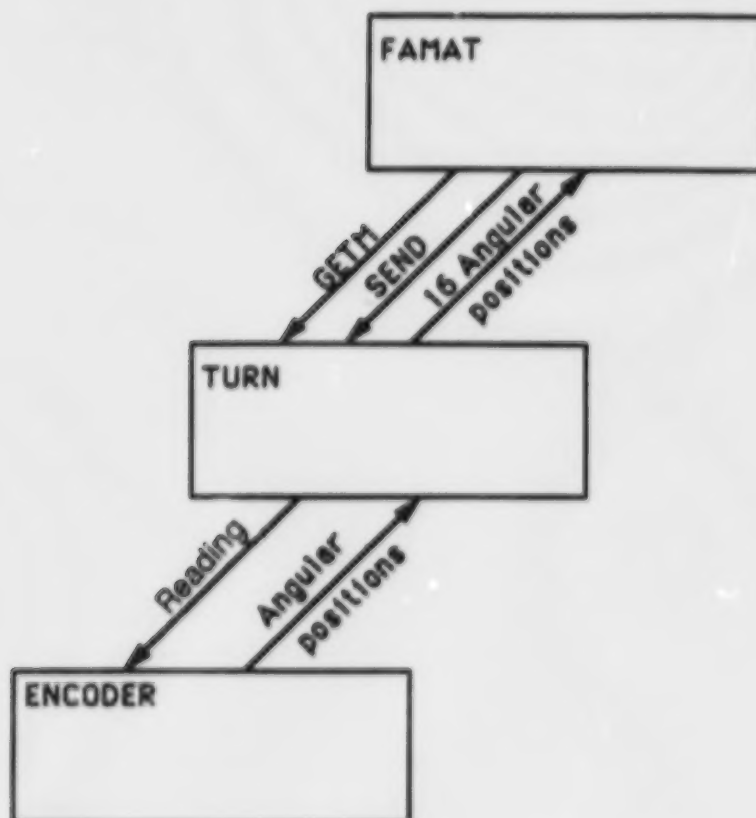


Figure 4.5.7 Control/data flow for current system

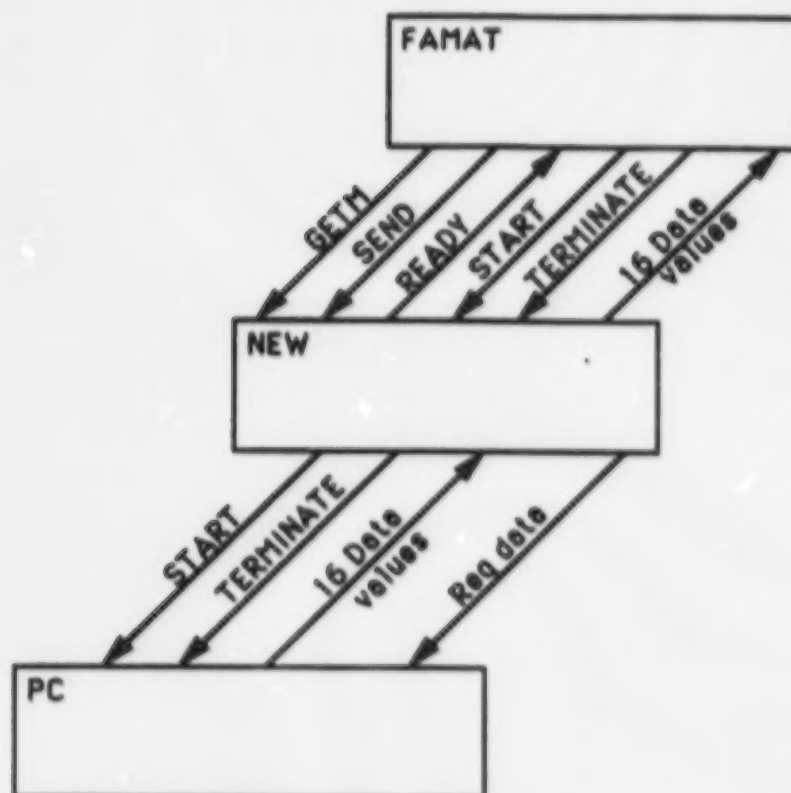


Figure 4.5.8 Control/data flow for the proposed system

Upon receipt of this command the PC stops sampling and begins to interpolate the processed data. Once the processing is completed the results are transmitted to the MLS unit over the RS232C link. At the MLS unit the received results are stored under the control of the task NEW. When all the data is gathered FAMAT is informed of this by means of the semaphore READY. In response FAMAT, transmits the semaphore SEND indicating that it is ready to receive the data. Once NEW receives the semaphore it sends all the data in the mail to FAMAT. A more detailed description of the interface has been deferred to Appendix A2.0.

4.6 SUMMARY

The proposed mobile MLS CTF consists of a calibration antenna suspended on a retractible mast. As will be detailed in section (6), this mast is mounted on a truck which contains the MLS processor. The calibration antenna measures the signals emitted by the MLS phased array and passes this information to the MLS processor. The proposed tracking system measures the deflection of the calibration antenna during the RF data gathering period and conveys this information to the MLS processor via a telemetry link. The processor uses this information to account for the error introduced by this deflection when calculating the beam pointing accuracy of the MLS phased array under test.

Several implementation options such as radar, sonar, tracking theodolites and optical trackers were investigated. The criteria used to evaluate each of these options include: portability, availability, operator interaction, and the error introduced by each system.

The optical tracker was selected for implementing the proposed system. The reason for selecting this design was it's innovative processing technique which eliminates the need for constant tracking of the target. This system also has a positional physical accuracy which is much greater than that obtainable from any other commercially available system that we were able to locate. Also, this design does not impose any foreseen technological barriers, and all the subcomponents associated with this design are commercially available. Therefore, the amount of development and risk required to obtain a finished product is minimized. This system contains very little hardware so it can be made portable.

The optical tracking system consists of a video camera, tracking mount, framegrabber and a processing CPU. The video camera installed on the tracking mount is used to observe the deflection of the calibration antenna in its field of view, and focus the image onto a CCD array. The mount is used to point the camera to predefined points on the measuring grid. The tracking system is placed in an environmentally controlled enclosure and is controlled remotely by an operator located in a truck via a telemetry link. The tracking hardware outlined above can be oriented in several different ways. In this study two such options were analyzed, each of which are described below:

Option 1)

In this option the video images output by the camera are digitized using a framegrabber located at the remote site. These digitized images are input to a PC which in turn perform the appropriate calculations to obtain the location of the calibration antenna at the time instants desired by the MLS signal analyzer. The calculated results are then conveyed to the MLS processor via the telemetry link. This is the preferred option.

Option 2)

In this scenario the video images are transmitted to a PC located in the truck using a video link. Here the signals are digitized and processed to obtain the desired results.

Under the hardware orientation option mentioned above we believe that the adoption of Option 1 whereby all the hardware is located at the remote terminal represents the optimal balance between cost, complexity and user desirability.

The maximum allowable angular error for this system is $\pm 0.005^\circ$ while the calculation of the worst case error budget revealed an error of $\pm 0.0047^\circ$. Therefore, under the worst case scenario this system meets the maximum allowable error.

Certain precautions will have to be adopted to prevent the system from tracking spurious objects in the vicinity of the calibration antenna. This includes placing a coloured light on the calibration antenna and placing the corresponding coloured filter on the video camera. This in effect will force the tracker to only observe light emissions of the selected colour. Also, the processor will check the image of the tracking light for multiple targets, and notify the operator if any are detected.

The digital interface of the tracking system to the current MLS signal analyzer could be designed in such a manner as to preserve the existing MLS Signal Analyzer hardware/software architecture if desired. The electrical interfaces associated with the tracking system could also be designed to be compatible with those of the existing MLS Signal Analyzer system.

A system using the aforementioned conceptual design would yield a robust, cost effective product which would meet the needs of the proposed tracking system.

5.0 ANTENNA MOUNT CONCEPTUAL DESIGN

The antenna mount is actually comprised of a number of sub-assemblies, each serving different functions. The vehicle mount attaches the antenna mast to the utility van. The mast is extended and retracted by a pneumatic system that is driven off of the van's electric power system. Joint stiffeners are used to both seal the gap between the telescopic sections, and to provide extra mast stiffness. A hazard light must be mounted at the top of the mast for safety reasons.

The micro-strip probe antenna on top of the tower must have a tracking light mounted at its phase centre for the tracking system to target. Finally, a fine motion mechanism capable of moving the antenna continuously over ± 1.5 m is necessary to help determine the existence of multi-path effects.

The conceptual design of the antenna mount can be divided into several subsections as outlined below:

5.1 VEHICLE MOUNT

The retractable mast must be suitable for mounting on the rear of a commercially available mini or, mid sized van as illustrated in Figure 5.1. When the vehicle is in motion off-site, the retracted mast will be stowed in a reclined position on the roof of the van. When deployed the extended mast will be secured to the frame of the van by means of a specially designed support fixture. In all two such fixtures will be designed. They will take the place of the bumpers and will be directly attached to the frame of the vehicle. To facilitate ease of transport these fixtures must be designed so that they can be easily removed and housed within the vehicle. The support fixtures also incorporate levelling and stabilizing jacks which can be operated remotely from the driver's seat. These jacks will level the vehicle prior to the collection of R.F data. A lateral load will also be applied to the mast by a guy wire tensioned about a vertical post attached to the front support fixture. This pre-tensioning of the mast significantly reduces its sway under wind. When the mast is reclined the slack in the guy wire will be gathered by a rewind spool located at the top of this post. A locating pointer suspended from this support fixture will be used to position the vehicle on various points of the predefined measuring grid. A secondary support fixture mounted on the roof of the van is also used to support the mast in both the extended and reclined positions.

A cable wound along the length of the mast connects the calibration antenna to the MLS Signal Analyzer located in the van. This cable also provides power to a hazard warning light and control lines to a stepper motor located at the top of the mast. The stepper motor controls the vertical movement of the calibration antenna which allows for the detection of multipath effects. When the mast is reclined the slack in the cable will be gathered by a rewind spool located on the roof of the vehicle, or else it will be helically wound around the base of the mast.

5.2 HAZARD LIGHT MOUNTING

A weatherproof hazard light will be mounted on the top of the mast to meet airfield requirements.

5.3 TRACKING TARGET

A tracking light mounted at the centre of the calibration antenna will be used by the optical tracker to determine the exact location of this antenna at any instant of time. In fact, if a planar micro-strip antenna is used, and is designed such that its phase centre is centrally located on its surface, then the tracking light should be mounted at the phase centre. In this case, the tracking system will always measure the position of the probe antenna's phase centre independent of any rotational motion of the tower. The light will be selected for compatibility with the tracking camera so as to avoid confusion with other light sources in the vicinity. Depending on the physical size the light source it will be either mounted on the front or the back of the antenna. If excessive optical distortion is noticed a set of lenses may be placed in front of the source to reduce the effect of this distortion.

The probe antenna must be a planar (have a planar surface) antenna such as a single horn, an array of horns, a slotted waveguide array or a microstrip array. An endfire array would have its phase centre somewhere between the input end and its tip. It would be very hard to place a tracking light in the correct position without degrading its electrical performance. A parabola with or without struts would have a shifting phase centre because the shadowing of the feed and struts on the reflector surface will shift with aspect angle.

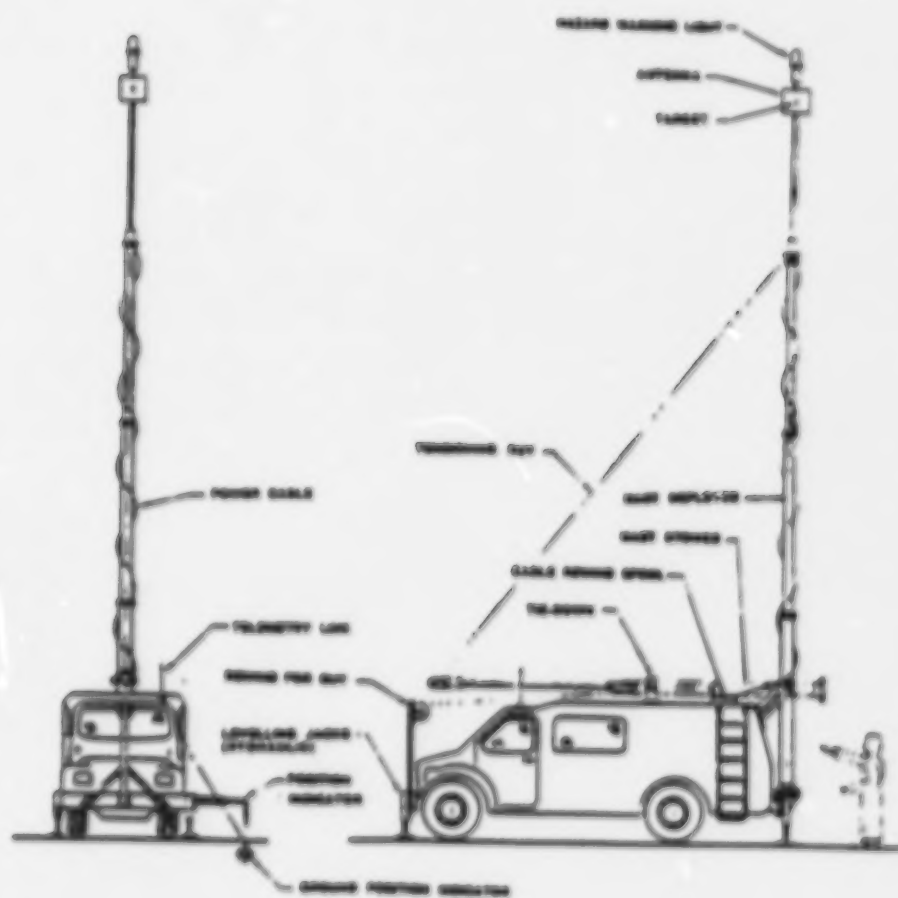


Figure S.1 Orientation of Mast on Truck

5.4 FINE MOTION

To determine the presence of multipath effects a fine motion mechanism is incorporated at the top of the mast. This mechanism permits continuous motion of the probe antenna over a ± 1.5 m distance. This mechanism illustrated in Figure 5.2 is responsible for the vertical positioning of the calibration antenna over a one metre range. The positioning of this antenna is controlled by the operator located in the van. To prevent the calibration antenna from rotating about the axis of the mast, the antenna is restricted to moving in a vertical slot cut in the top section of this mast.

5.5 JOINT STIFFENERS

The retractable mast will consist of several telescoping sections of aluminium tubing. The mast will not be fitted with stock locks to hold it in the raised position. This is because the mast is required to be held raised for only a very short period for each reading to be taken and also may need to be retracted quickly in an emergency to depart from the test area.

To minimize sway due to play in the joints the joint stop at the top of each section will incorporate a unique 45 degree wedge feature as illustrated in Figure 5.3. This design will also avoid any likelihood of the mast "sticking" in the extended position.

5.6 MAST EXTENSION AND RETRACTION

The mast will be extended using a pneumatic pump run directly off the van's 12 V electrical system. Extension and retraction can be controlled from the driver's seat. Retraction of the mast is damped by a bleeder valve which restricts the flow of air out of the mast such that the mast retracts at an optimum, controlled rate.

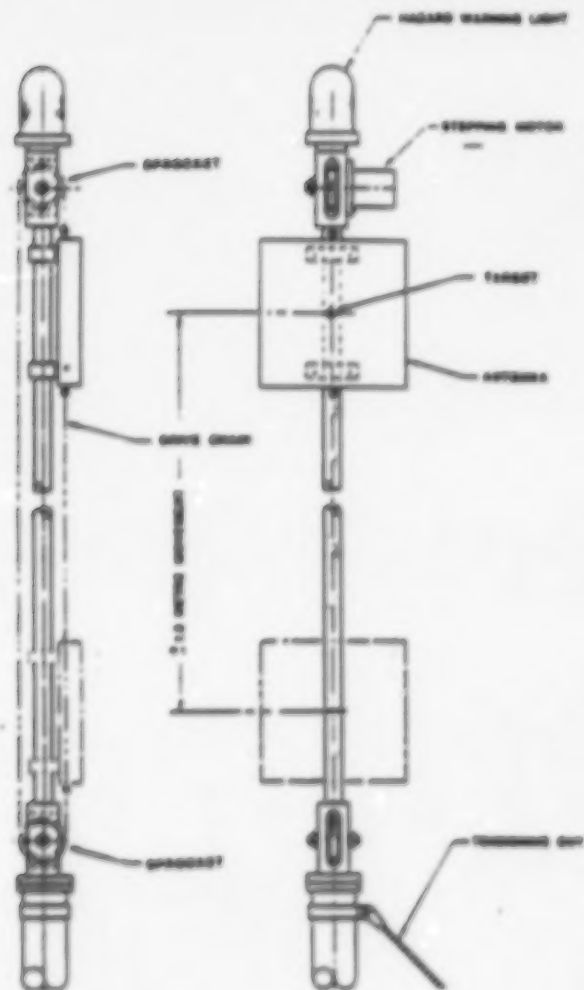


Figure 5.2 Fine Motion Mechanism

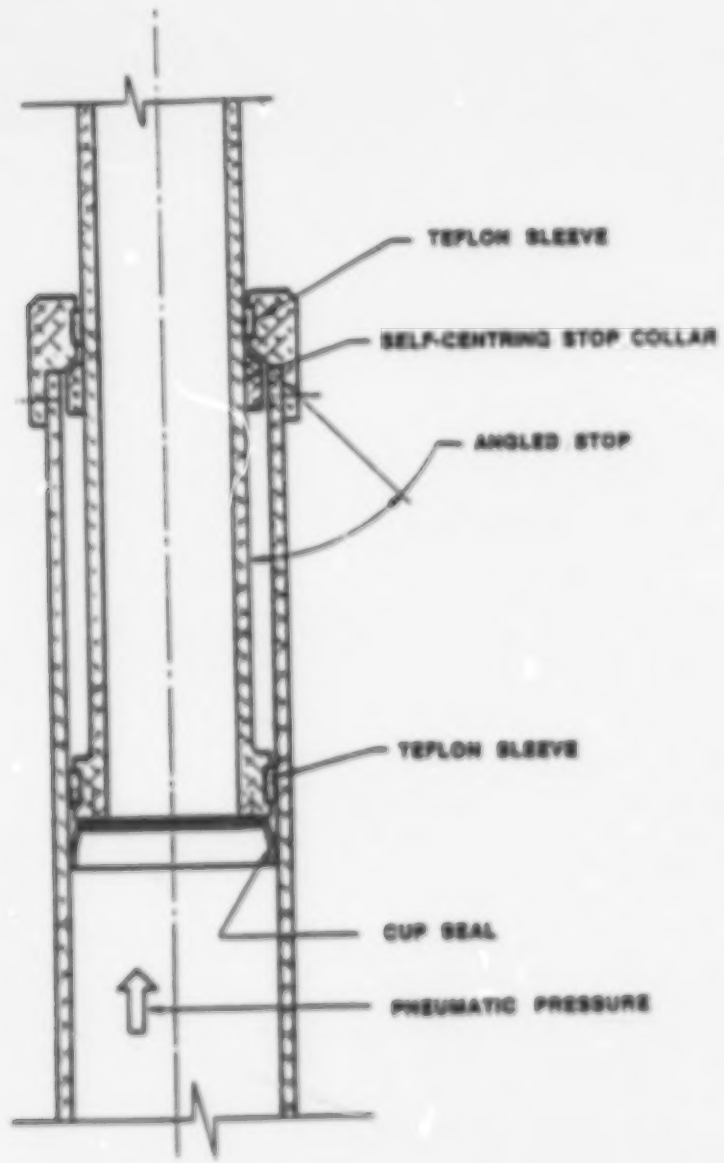


Figure 5.3 Joint Structure for the Proposed Mast

6.0 MLS ANTENNA PROBE PRECISION PLACEMENT SYSTEM CONCEPTUAL DESIGN

The proposed mobile MLS tracking system illustrated in Figure 6.1 consists of 2 major components:

- i) A 15.25 m high retractable mast mounted on the roof of a medium sized van which houses the CTF processor.
- ii) A optical tracking system housed in a environmental enclosure mounted on the MLS antenna under test.

The telescopic design of the retractable mast enables adjoining section to collapse into one another thereby giving a total retracted length of less than 3.36 m. When this unit is being transported from one measurement site to another the retracted mast will be stowed in a reclined position on the roof of the van. Site measurements will be conducted with the mast in the extended, upright position. As data has to be gathered from various locations on a particular test site the mast will be retracted for safety reasons, when moving between measurement points.

The tracking system consists of a remotely controlled tracking mount with a video camera system (a telescopic lens, a CCD array and a frame grabber) mounted on it. The camera is used to observe the position of the calibration antenna while the mount is used to position the camera to various points on a predefined measuring grid. Under normal operation the calibration antenna which is mounted on the retractable mast samples the R.F. signals emitted by the MLS antenna under test. This data is input to the MLS signal analyzer located in the van where it is used to determine the beam pointing accuracy of the antenna under test. As the beam pointing accuracy of the MLS antenna has to be known to high precision, the deflection of the calibration antenna during the RF signal measurement period has to be quantized and taken into account. The optical tracking system provides a means by which this deflection can be measured. The action of the tracking system is controlled by an operator located in the van.

To assess the proper functioning of an MLS antenna, data has to be gathered from several locations on the predefined measuring grid. Each point on this grid is defined relative to a surveyed point in the vicinity of the MLS antenna. The shape of the measurement grid proposed for this system is illustrated in Figure 6.2. The measurement process is initiated by moving the van to the desired location on the grid. Course positioning of the van with respect to the desired measurement point is achieved by aligning this point with a pointing stick suspended from the front support fixture on the driver's side of the van. Once the van is correctly positioned it is levelled using four hydraulic jacks located

at each corner of the van. The purpose of the hydraulic jacks is not only to level the vehicle but also to provide a stable platform on which the mast can be extended. When the levelling process is complete the mast is extended using a pneumatic pump. The mast is secured at the base by a specially designed support fixture which is directly attached to the frame of the vehicle. To limit lateral deflection a fixed resistance guy will be attached between the front support fixture of the vehicle and the top of the mast. When the mast is extended and properly secured the operator informs the tracking system of the present grid co-ordinates. The tracker responds by moving to the specific location and sampling several images. It then uses these images to determine the presence of multiple targets. If multiple targets are detected the operator is informed of this and a search routine is initiated at the operator's discretion. Once the calibration antenna is located and centred with respect to the tracker's field of view the R.F. data sampling process is initiated. During this period the calibration antenna samples the R.F. signals emitted by the MLS antenna while a video camera mounted on the tracking system monitors the movement of the calibration antenna. The analogue output of this camera is digitized and then processed to determine the positional offset of the calibration antenna during the R.F. data sampling period. This data is then input to the MLS signal Analyzer unit which uses it to determine the beam pointing accuracy, and other parameters, of the MLS antenna under test. This measurement process is repeated at several locations on the test site to obtain an accurate assessment of the MLS antenna's beam pointing capabilities.

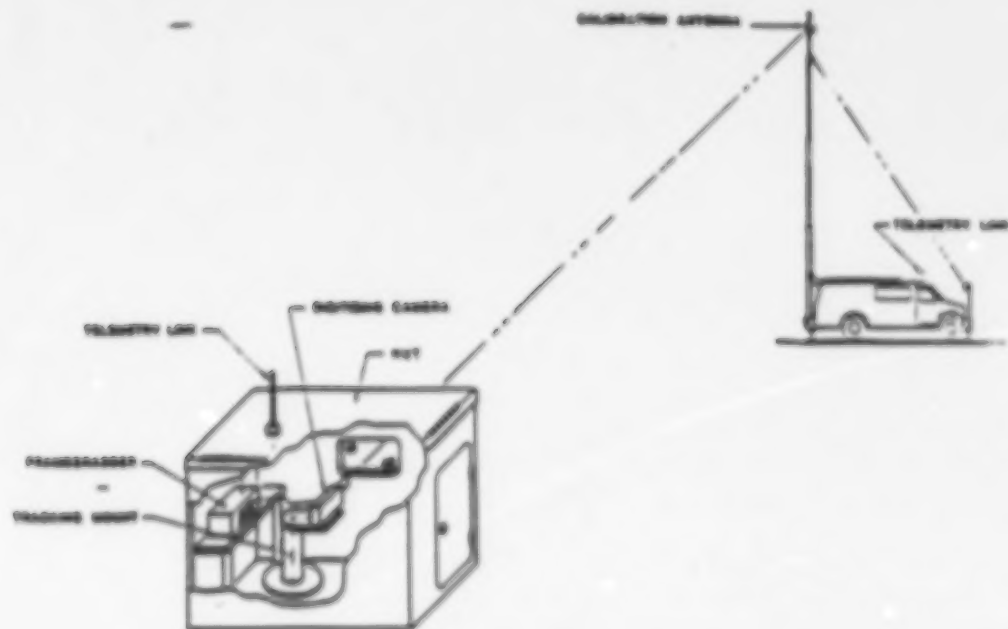


Figure 6.1 Mobile MLS CTF System

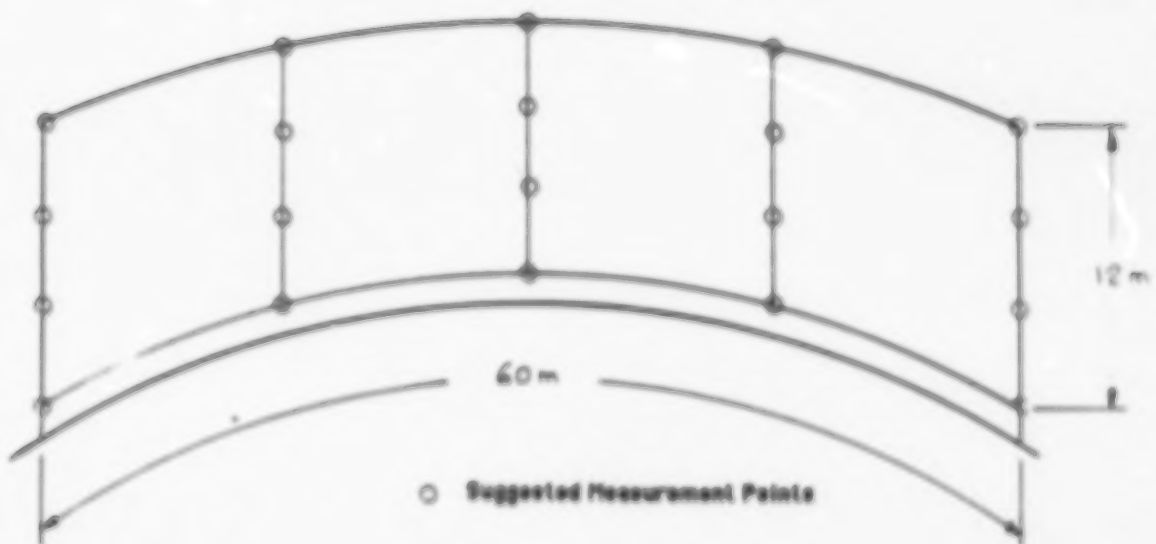


Figure 6.2 Test Measurement Zone

A1.0 APPENDIX

A1.1 STABILITY ANALYSIS

Nomenclature

The following nomenclature is used throughout this appendix and is summarized here for convenience and conventions.

$\delta x'$	-	displacement in x' - direction (m)
$\delta y'$	-	displacement in y' - direction (m)
$\delta z'$	-	displacement in z' - direction (m)
δx	-	displacement in x - direction (m)
δy	-	displacement in y - direction (m)
δz	-	displacement in z - direction (m)
v	-	velocity of wind (m/s)

In all of the models it is assumed that the height of the antenna is 15.25 m and that the antenna is 0.0929m² in area.

It is also assumed in all calculations that the winds are in the worst case direction (at right angles to the probe antenna).

Stability Requirements

Based on the maximum permitted angular errors (0.005°) as discussed in the text, the displacement of the mast, illustrated in Figure A1.1, should not exceed the values stated below.

$$\begin{aligned}\delta x' &\pm 3 \text{ mm} \\ \delta z' &\pm 3 \text{ mm}\end{aligned}$$

The geometry is such that the mast will have little motion in vertical direction, thus the coordinates as illustrated in Figure A1.2 are more amenable to the following analysis.

In the unprimed coordinate system, the deflection in the y -direction will be limited by the z' requirements:

$$\delta z' = \delta y \sin \phi \quad -(1)$$

$$\text{where } \sin \phi = \frac{15.24}{\sqrt{45^2 + 15.24^2}} = 0.32$$

$$\delta x' = \delta x \quad -(2)$$

ϕ is defined in Figure A1.3

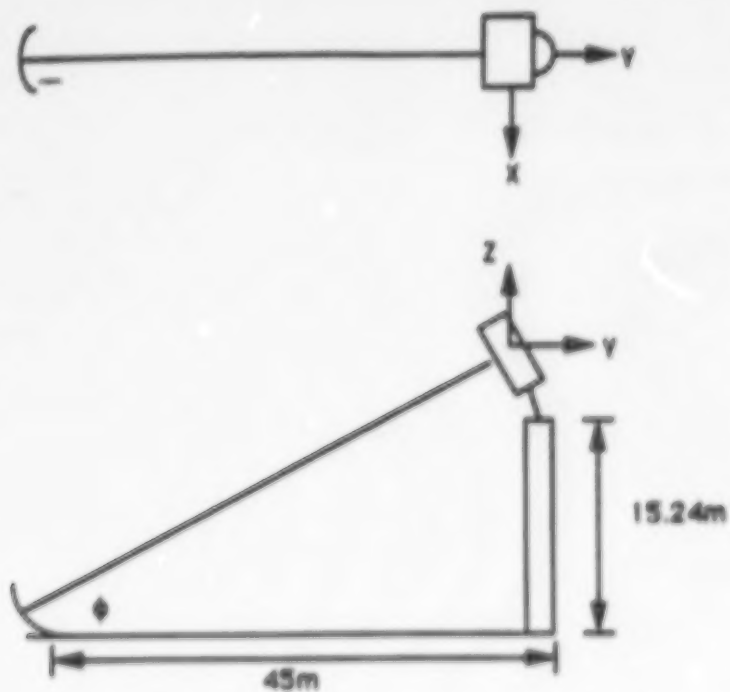


Figure A1.1 X,Y,Z Co-ordinate System

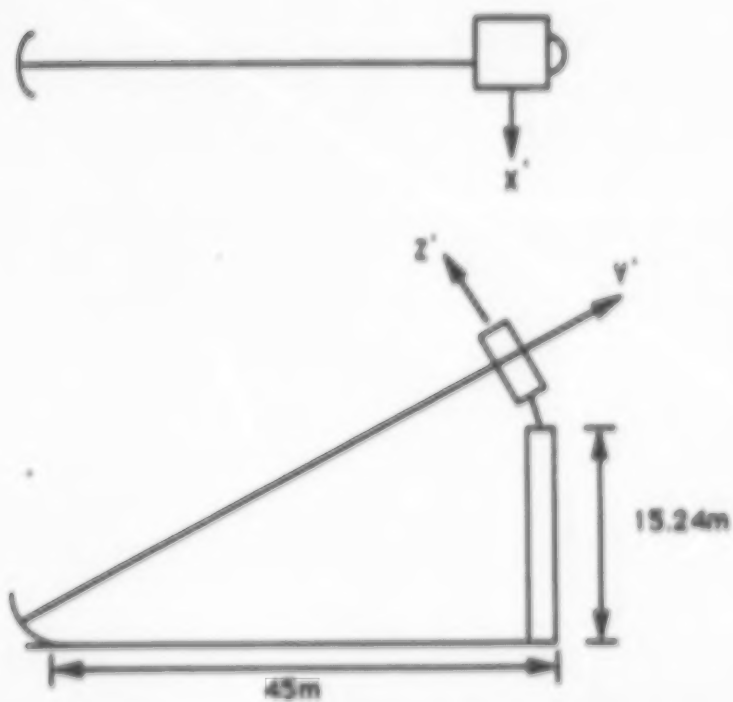
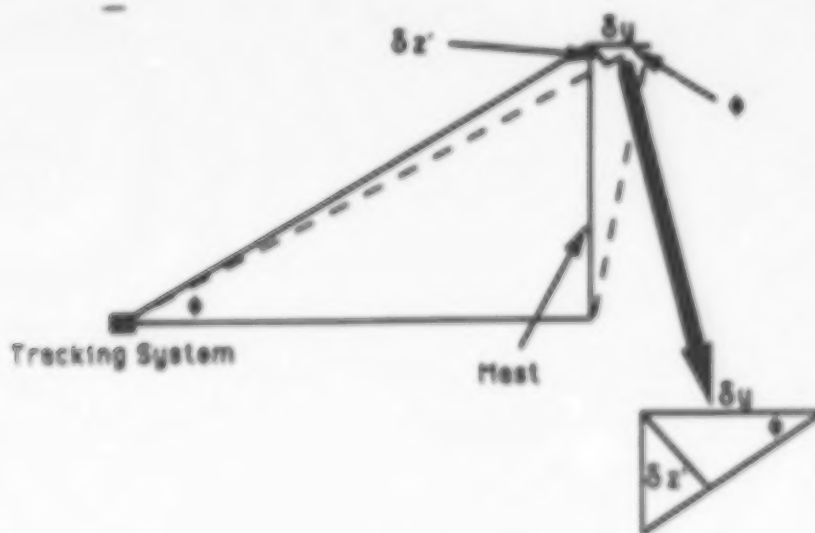


Figure A1.2 X',Y',Z' Co-ordinate System

Figure A1.3 Definition of ϕ

Substituting $\delta z' = 3 \text{ mm}$, $\delta x' = 3 \text{ mm}$ and $\sin \phi = 0.32$ into the equations (1) and (2), the following is obtained.

$$\begin{aligned}\delta x &= 3 \text{ mm} \\ \delta y &= 9.3 \text{ mm}\end{aligned}$$

Windforces on Antenna

Since the calibration antenna is flat, and faces the transmitting MLS antenna under test, the effect of the wind on the calibration antenna is only in the direction perpendicular to the wind.

Deflection models were developed for the following masts:

- 1) Unguyed, solid aluminum alloy, constant cross section, rigidly fixed to the ground
- 2) Unguyed, solid aluminum alloy, tapered cross section, rigidly fixed to the ground
- 3) Unguyed Racal tower - RA458, 7 sections
- 4) Guyed Racal tower - RA458, 7 sections

In this analysis the deflection undergone by each model was assumed to be due to a uniform wind force applied along the entire length of each mast. The wind velocity was calculated, using data presented in Table 1-2, to be 30 km/h. This value represents the weighted average of the annual wind velocities observed at Ottawa International Airport on a month to month basis.

Summary of Results

Model 1 - unguyed, solid, aluminum alloy, constant cross section, rigidly fixed to earth. In this model, the following parameters were defined.

d - diameter of mast (m)
 v - wind velocity (km/h)

The deflections of the mast in the x and y axes were calculated and are given below:

$$\delta x = 1.185 \times 10^{-6} \frac{v^2}{d^3} \quad (3) \quad \delta y = 1.249 \times 10^{-6} \frac{v^2}{d^3} \quad (4)$$

Using these equations the dimensions of the mast can be calculated as a function of the tolerable deflection in either axis, and the wind velocity v . For example if:

$$\begin{aligned} \delta x &= 3 \text{ mm} \\ v &= 30 \text{ km/h} \end{aligned}$$

then the diameter of the mast can be calculated by substituting these values into equations (3).

Therefore the minimum diameter of the mast should be :

$$d = (1.85 \times 10^{-6} \cdot 8.33^2 / 3 \times 10^{-3})^{1/3} = 0.302 \text{ m}$$

The size of the mast required for a 3 mm deflection is seen to be such too large to be practical.

Model 2 - unguyed, aluminum alloy, solid, tapered cross section, rigidly fixed to the earth.

In this model:

d_1 - Top diameter of mast (m)
 d_2 - Bottom diameter of mast (m)

The deflection of the mast in the x-axis is given by the following equation:

$$\begin{aligned} \delta x = f_1 & \left(7.90 \times 10^{-7} \frac{v^2}{d_1^3} + 3.95 \times 10^{-7} \frac{d_1 v^2}{d_1^4} \right) \\ \delta x = f_1 & \left(7.90 \times 10^{-7} \frac{v^2}{d_1^3} + 3.95 \times 10^{-7} \frac{d_1 v^2}{d_1^4} \right) \\ & + f_2 \left(6.358 \times 10^{-8} \frac{v^2}{d_1^3} \right) \quad (5) \end{aligned}$$

where:

$$f^1 = y_A - \text{Roark's formulas for stress and strain by Warren C. Young, Table 13d - 2a, uniform increase, } a = 0, \frac{I_B}{I_A} = \frac{d_B^4}{d_A^4}$$

$$f^2 = y_A - \text{Roark's, formulas for stress and strain by Warren C. Young.}$$

$$\text{Table 13d - 1a, } a = 0, \frac{I_B}{I_A} = \frac{d_B^4}{d_A^4}$$

When the appropriate numbers are substituted into the above equation the result obtained indicate that the dimensions of the mast are too large for all practical purposes.

Model 3 - unguyed Racal Tower - RA458, 7 sections

The deflection of the tower was calculated using a method similar to a finite element analysis, whereby the deflection of each section of the mast was calculated individually and then combined to obtain the total deflection. The behaviour of the mast in the x and y axes can be described using the following equations:

$$\delta y = 1.09 \times 10^{-8} \frac{v^2}{E} \quad (6)$$

$$\delta y = 1.43 \times 10^{-8} \frac{v^2}{E} \quad (7)$$

for aluminum the elasticity of modulation, $E = 71\text{GP}$.

Substituting this value into equations (6) and (7) the following is obtained

$$\delta x = 1.54 \times 10^{-3} v^2 \quad (8)$$

$$\delta x = 1.54 \times 10^{-3} v^2 \quad (9)$$

For a wind velocity of 30 km/h (i.e. 8.33m/s) the deflection of the mast along the x axis is calculated to be:

$$\begin{aligned} \delta x &= 1.54 \times 10^{-3} \times 8.33^2 \\ &= 107 \text{ mm} \end{aligned}$$

The deflections of this mast at other wind speeds are illustrated in Table A1.1.

Table A1.1 - Deflections of an Unguyed Rascal Tower

V (m/s)	$\delta x, \delta x'$ (mm)	δy (mm)	$\delta x' = \delta y \cos \phi$ (mm)
2	6.2	8.0	2.6
4	24.6	32.2	10.3
6	55.4	72.4	23.2
10	154.0	201.0	64.3
15	346.5	452.3	144.7

Note $6'' = 152.4 \text{ mm}$

The mast, although practical to implement, yields deflections under wind that exceeds the system requirements. Therefore it would have to be used in conjunction with a tracking system.

These deflections of the mast could greatly be reduced by use of guy wires.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
<75	100	100	100	100	100	100	100	100	100	100	100	100	<20.0
<42	100	100	100	100	100	100	100	100	100	100	100	100	<17.0
<50	99.8	99.8	99.9	99.9	100	100	100	100	100	100	100	99.8	<13.0
<30	97.8	98	97.5	98	99.2	99.6	99.9	99.9	99.7	99.2	98.5	98	<10.0
<29	89.5	89.2	87.2	88.6	92.6	96.5	98.1	98	96.6	94.5	91.5	90	<8.1
<20	70.3	70.2	68	66.6	76.5	82.3	87.5	88	83.3	78.2	74.1	71.6	<5.6
<12	27.2	27.5	26.1	22.2									<3.2
<6	9.7	9.9	9	7.2									<1.7

Table A1.2 - Wind Velocity Measured at Ottawa Airport

Model 4 - guyed Racal Tower - RA458, 7 sections

Equations describing the deflections of the mast in the x and y axes were derived and are given below:

$$\delta x = \frac{A_1 x^2}{AE} \quad (10)$$

$$\delta y = \frac{A_2 y^2}{AE} \quad (11)$$

where:

A is the cross sectional area and, E is the modulus of elasticity of the guying cables

For both steel and spectra (a non-metallic flexible composite material) cables:

$$E = 24,000 \text{ ksi;}$$

$$\text{or } E = 1.654 \times 10^{11} \text{ Pa}$$

also $A = 0.45 d^2$ where d is the diameter of the cable.
 Substituting these values into equations (10)
 and (11) the following is obtained:

$$\delta x = 6.54 \times 10^{-11} \frac{v^2}{d^2} \quad (m) \quad -(12)$$

$$\delta y = 7.73 \times 10^{-11} \frac{v^2}{d^2} \quad (m) \quad -(13)$$

$$\text{eg: } d = 1.23 \times 10^{-3} \text{ m} = 1.23 \text{ mm } \approx 3 \text{ mm}, v = 30 \text{ km/h}$$

For wind velocity of 30 km/h, and an allowable mast deflection of 3 mm along the x-axis, the minimum diameter of the cable can be calculated by substituting these values into equation (12).

The minimum diameter of the cable is:

$$d = \sqrt{6.54 \times 10^{-11} \times 0.33^2 / 3 \times 10^{-3}} = 1.23 \times 10^{-3} \text{ m}$$

As this thickness of cable is suitable for practical use, it is evident that a guyed system would be capable of supporting the probe antenna, in winds, to within allowable tolerances.

A2.0 APPENDIX

A2.1 DETAILED DESCRIPTION OF THE TRACKING INTERFACE

Figure A4.1 details the signal/data diagram for the mobile MLS system. When the MLS unit is powered up it sends an INIT command to the PC. If the PC is powered up it begins to initialize itself upon receipt of this command. One of the tasks under the initialization process is to send an INIT ACK to the MLS system. If an INIT ACK is not received by the MLS system a certain time delay after the transmission of INIT command then the system times out and retransmits this command. Once the INIT ACK is received by the MLS it transmits a MOVE command along with co-ordinates it wants the tracking mount to point to. When these commands are received by the PC it moves the tracking mount to the desired co-ordinates. At this location the PC samples several frames of data. It then checks these frames to determine whether other objects such as background lights are present on the image. If the antenna is absent from the image then the operator is informed of this, and a search routine is activated to locate the antenna. When the antenna is located the system performs a final check to determine the presence of multiple targets. If multiple objects are detected the operator is informed of this by means of an error message. Further processing is terminated until this ambiguity is resolved or the tracker is moved to a new position. If no other objects are detected then the PC calculates the fixed offsets from the middle of the image to the centre of the light mounted on the calibration antenna. These offsets are then conveyed to the MLS system. If the offset is too large in either the azimuth or elevational planes then the MLS issues a new move command with the corresponding co-ordinates. If however the offset is within tolerable limits then NEW issues a RDY SAMP semaphore to FAMAT indicating that the PC is ready to begin sampling data. FAMAT responds to this request by issuing a START command. This command is conveyed by NEW to the PC. Upon receipt of this command the PC transmits a sample ACK to the MLS and then begins to sample the video data. The sampled data is processed and time tagged prior to being stored in a buffer. When FAMAT requires a positional update of the calibration antenna it sends a GETM semaphore to NEW. NEW conveys this message to the PC in the form of a DATA REQ. At the PC these DATA REQ. are time tagged and placed in a buffer. Data sampling is terminated by FAMAT which issues a terminate command. This command is conveyed through NEW to the PC. When the PC receives this command it terminates the sampling process and then begins to interpolate the stored data. For a detailed look at the processing and interpolation aspects involved with this design please refer to section 4.5.1. The results generated from this interpolation process are transmitted over the RS232C link to the MLS unit. These results are then stored in a buffer under the control of the task NEW. Once all the data is transmitted the PC issues

a COMPLETE command to denote the completion of the transmit process. - When NEW receives this command it sends a READY signal to FAMAT to indicate that it is prepared to send the results. FAMAT acknowledges this by issuing a SEND command. Once NEW obtains this semaphore it places all the results in the mail and sends them to FAMAT. FAMAT uses these values to compensate for any shifts in the calibration antennas that may have been present during the measurement process.

The OUT semaphore is used by both tasks to interface with the output console.

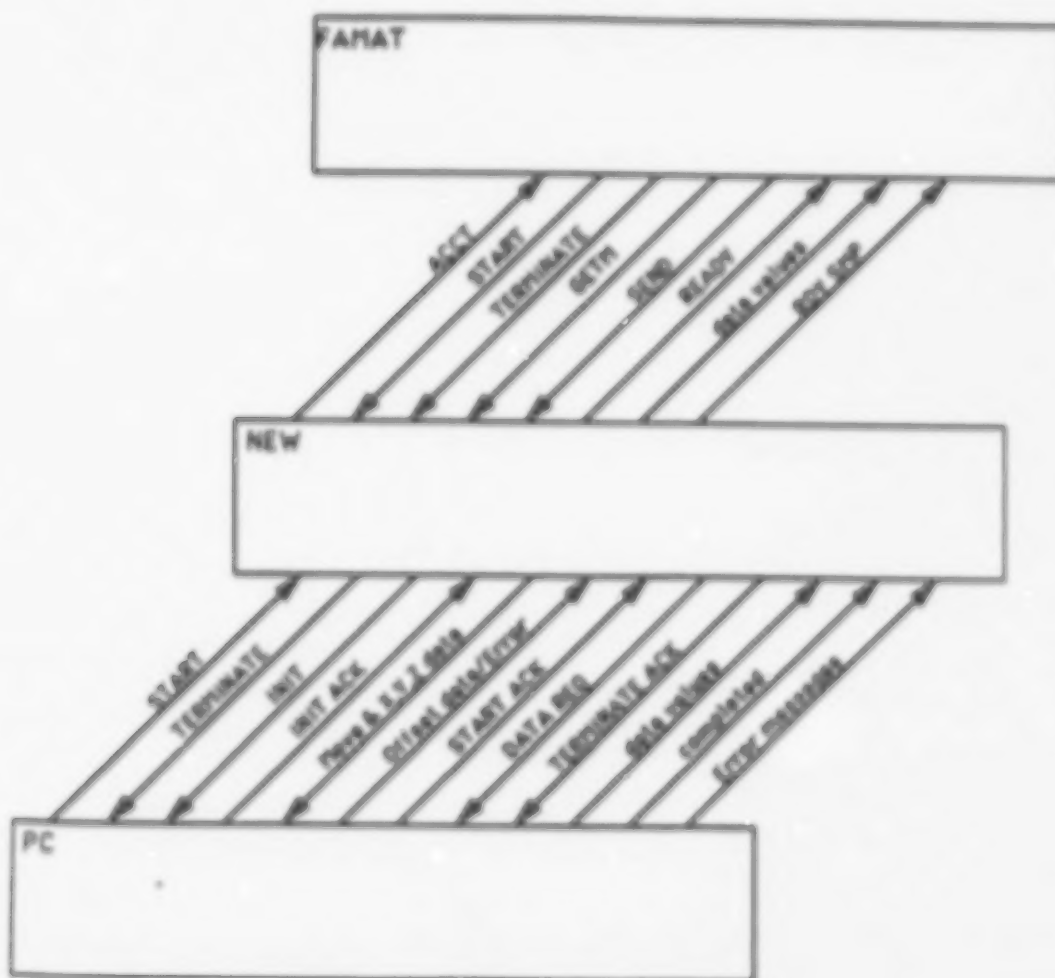


Figure A2.1 Detailed control/data flow diagram for the proposed system

A3.0 APPENDIX

RESOLUTION OF OPTICAL CCD ARRAYS

The resolution maybe expressed as the modulation depth of a CCD array output signal that arises from a black and white bar pattern imaged on the device. This parameter is often referred to as the Modulation Transfer Function (MTF) of the device. The following general properties of CCD array resolution hold for "normal" operation.

The resolution in the two CCD imaging dimensions are slightly different, as a result of the CCD array construction. In both dimensions, the resolution approaches 100% of its theoretical value (based on element spacing) for coarse image detail.

For the case in which the CCD pixels are separated by the charge transfer columns (as defined by the channel-stop regions) the MTF falls to approximately 64% as the image detail spacing approaches that of channel-stop regions. Finer detail than this pixel spacing cannot be resolved unambiguously in this dimension as it would contravene the Nyquist sampling theorem.

Without interlace, the fine resolution in the orthogonal direction would be similar, that is it would be limited to the CCD element spacing. However, as in this dimension each CCD element is comprised of two cells, it is possible to use the technique of interlacing. With interlace, each CCD element is used to form, in effect two photo sites, with the result that the Nyquist sampling rate is increased. Consequently, the resolution (MTF) is relatively better in this dimension as the image detail approaches the CCD element spacing.

Other factors that degrade the resolution include CCD cell saturation, and inefficient charge transfer. It is possible, however to control the CCD optical exposure such that saturation does not occur.

The inter-cell "leakage" that may take place between CCD arrays can reasonably be expected to be small, and symmetrically distributed. Consequently, its effect should vanish when curve fitting techniques are applied to determine the centre (point of a maximum intensity) of an illuminated strip of cells, as would be the case for the application applied here.